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The Metric of Binocular Visual Space*

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The aim of this paper is to show that the so-called visual space has a uniquely determined non-Euclidean metric, or psychometric distance function, the numerical parameters of which depend on the individual observer. Certain well-known phenomena of space perception, such as the horopter, the alley experiment and size constancy, are explained on the basis of the distance function. Methods of measuring the personal parameters of the metric are developed, and applications of the theory to the field of binocular instruments and pictorial representation of space are suggested.

1. PURPOSE

VISUAL sensations are established under the influence of many different factors. They are the result of an activation of our mind by physical light stimuli and are distinguished by a remarkable degree of certainty and definiteness which tempts us to believe that the external world itself is revealed to us, and not merely an image of our own making. Through vision, external objects are presented to us in a three-dimensional continuum, endowed with certain sensed qualities of color, brightness, form, and localization.

Yet it is well known that the final form of visual sensations actually depends on the observer's psychological condition which in turn is the result of his entire personal development, his former experience, his prejudices, even his instantaneous wishes and intentions.

Recognition of this fact does not mean that all attempts of a quantitative investigation of visual perception must be abandoned. Visual sensations are not merely the chance result of coincidental psychological conditions but are governed by certain constant factors which, though not determining the sensations completely, play an integral part in their formation. These factors must be related to the external physical situation as well as to certain constant elements in the personality of the observer. The denial of the existence of such constant elements in the relationship of a living organism to external nature would be tantamount to denying all objectivity in visual sensations and therefore would be absurd.

In the following we are concerned with a special group of constant elements in visual sensations, namely, those which influence the sensed qualities of *form* and *localization* in the three-dimensional continuum of visual perception. Our aim is to show that this continuum, the so-called *Visual Space*, is a metric mathematical space. It possesses a uniquely determined metric, which varies in its numerical parameters from observer to observer. But its general form is invariant; it is the metric of the three-dimensional hyperbolic geometry.

2. CONSIDERATION LIMITED TO BINOCULAR FACTORS OF VISUAL PERCEPTION

This surprising conclusion is arrived at by an inductive analysis of certain experimental facts which are obtained under simplified laboratory conditions. The observations are made in a dark room with the observer's head, and therefore approximately also the rotational centers of his eyes, fixed by means of a

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† This is the last paper Dr. Luneburg wrote before his sudden, unexpected death in August, 1949. It was not written for publication and has been edited by the Knapp Laboratory staff working on this project and chiefly by Paul Boeder, consultant to the project. The paper is believed to be of great significance because here for the first time, Luneburg removes the restriction on freedom of observation and introduces the probable mathematical function involved in motion.

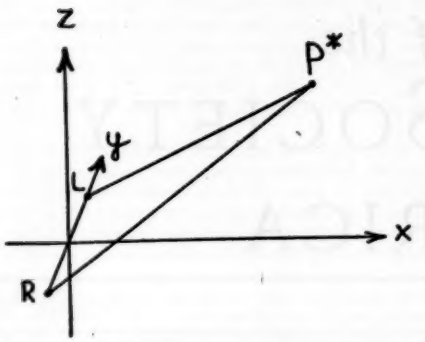

FIG. 1. Cartesian coordinate system for physical space; L and R represent centers of rotation of left and right eyes.

headrest. Let us assume that the centers of rotation, R and L, are the points $y=\pm 1$ of the y axis of a Cartesian coordinate system whose x, y-plane coincides with the physical horizontal plane (Fig. 1).

Simple geometrical configurations are presented to the observer; for instance, isolated light points, lighted lines or surfaces. In judging such configurations, the observer has to rely almost entirely on his primitive ability to see; intellectual clues of interpretation are practically excluded. We may assume that visual sensations such as these reveal more clearly the underlying constant factors which we wish to investigate.

There is a great difference between monocular and binocular vision under the artificial conditions just described. With one eye our judgment of spatial form and localization is erratic and inconsistent. Binocular observation, on the other hand, retains a high degree of certainty. True, in ordinary situations monocular observation is not necessarily inferior to binocular vision. But from experiments in the dark room we conclude that binocular vision adds certain elements to visual perception which monocular vision lacks. This is also demonstrated in a stereoscope which provides a situation of clueless vision comparable to that of the dark room. With a stereoscope, the monocular observer is dependent on intellectual clues of perspective and interpretation, whereas the binocular observer obtains a striking sensation of depth.

The following investigation is concerned with these special binocular or stereoscopic factors of visual perception. No claim is made of a general theory of space perception, nor even of a theory of visual perception integrating binocular as well as other psychological factors. In spite of this limitation, the end result is not without significance for the broader aim inasmuch as it will make possible a precise characterization of the variations which may be caused by the instantaneous psychological condition of the observer.

3. FACTS REQUIRING RECOGNITION

A theory of binocular vision must account for the following experimental facts.

(a) A single isolated light point P^* is given in the dark room. Let x, y, z, be its physical Cartesian coordinates. The observer sees the point P^* as a "sensed" point P in his three-dimensional visual space. It has, at any instant, a definite localization in this space, relative to certain subjective planes of reference of the observer, and relative to an apparent center of observation. The fact that two eyes are involved in creating the sensation of the point P^* is not represented in the visual space. We may say that binocular observation in the physical space corresponds to an apparent monocular observation in the visual space. Besides an apparent center of observation, there are three planes of reference of which we are conscious, namely, the subjective horizontal plane, the subjective median plane, and the subjective frontal plane. Mathematically we represent this in a Euclidean space by means of a Cartesian coordinate system, ξ, η, ζ. The origin $\xi=\eta=\zeta=0$ represents the apparent center of observation, the ξ, η-plane the subjective horizontal plane, the ξ, ζ-plane the median plane, and the η, ζ-plane the frontal plane of the visual space. In general, these planes are correlated approximately to the corresponding physical planes, i.e. a point P^* in the x, y-plane is seen as a point P near the ξ, η-plane, a point P^* in the x, z-plane as a point near to the median plane (Fig. 2).

Since the point P^* is seen, at any instant, as a point P in some definite localization relative to the three subjective planes of reference, we might be tempted to search for a constant and necessary one-to-one correspondence between physical points and sensed points in the visual space. However such an attempt would fail, since it would mean that visual sensations are uniquely determined by the physical stimuli, independent of psychological factors. It would also be in disagreement with actual observations. Visual localization of an isolated, repeatedly shown, physical point P^* is found to be highly erratic. The point P seems to be floating in space indeterminedly, now it seems near, now far. This uncertainty of correlating visual and physical localizations becomes obvious if a similar experiment is made with a stereoscope. It is even possible to disturb the observer's judgment of localization with respect to the subjective reference planes, for example, by placing him on a slowly rotating chair.

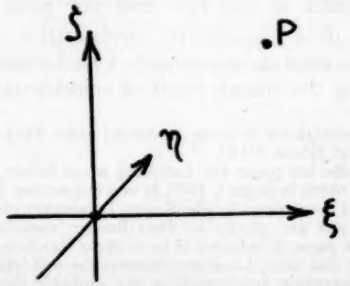

FIG. 2. Subjective coordinate system for visual space.

A point P seems to remain in the median plane, though the physical x, y-plane has been rotated into a different position.

The net result of experiments with an isolated point is purely negative: *Binocular observation of a single point does not differ from monocular observation.* Both are equally uncertain as to correlating a sensed point P to the physical coordinates of the stimulating point P^*.

(b) The situation is quite different when the object consists of several isolated points P_1^*, P_2^*, P_3^*, $\cdots$. Aside from sensing these points as points P_1, P_2, P_3, $\cdots$, in a three-dimensional continuum, we have a rather definite sensation of distance of the points from one another. We also find that the sizes of these sensed distances can be compared. Thus, denoting the sensed distance between two points P_1 and P_2 by (P_1P_2), our visual sensation of three points P_1, P_2, P_3 contains an immediate judgment of inequalities $(P_1P_2)>(P_2P_3)$ or $(P_1P_2)<(P_2P_3)$. The same is true for two pairs of points P_1, P_2 and P_3, P_4. There is an immediate perception of inequalities $(P_1P_2)>(P_3P_4)$ or $(P_1P_2)<(P_3P_4)$.

Moreover it is found, for binocular observation, *that the inequality signs are determined by the physical coordinates of the stimulating points* P_1^*, P_2^*, P_3^*, P_4^*. This means that the scores of repeated tests with the same two pairs of stimulating points are highly correlated, regardless of other physical qualities of the points such as brightness and color. A corresponding correlation is not found in monocular vision where such additional qualities may easily change our judgment. We note here that in general the sensed inequalities do not correspond to those between the physical distances $(P_1^*P_2^*)$ and $(P_3^*P_4^*)$. Moreover, there is no sensation of absolute localization of the whole configuration, that is, there is no certainty in judging the physical coordinates of the points P^* from the sensed coordinates of the points P.

(c) The following extremely interesting observation is due to Helmholtz.[1] An observer, placed into the position described previously, is given the task of arranging a number of light points so that they appear to lie on a horizontal straight line, symmetric to the median plane. It is found that the points are set consistently on certain physical curves which are, in general, not straight in the physical sense. The form of these so-called *horopter* curves depends on the distance x_0, of the center point. At a certain distance $x_0=a$ the horopter is practically straight. At nearer distances, $x_0<a$, the horopters are concave to the observer, at greater distances, $x_0>a$, they are convex (Fig. 3). The distance, a, of the straight horopter depends on the individual observer. The Helmholtz horopter experiment reveals a new element in visual sensations, namely, that there is an *immediate feeling for straightness* which allows us to judge whether *three points PRQ lie on a subjective straight line.*

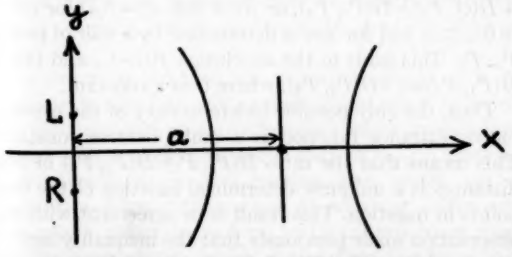

FIG. 3. Horopter curves for different fixations.

[1] H. V. Helmholtz, *Treatise on Psychological Optics*, J. P. C. Southall, Editor (Optical Society of America, 1925), Vol. 3, pp. 482 f.

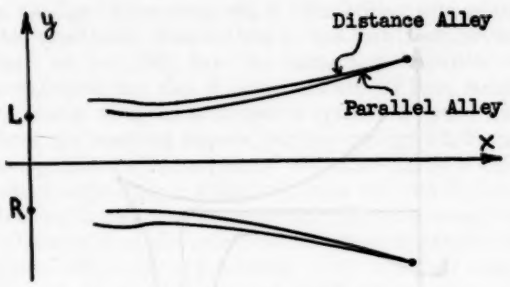

FIG. 4. Distance and parallel alleys.

(d) A related experiment was made by Hillebrand; it is the so-called *Alley experiment.*[2] It is well known that physically parallel lines like railroad tracks, or the curbs of a straight road, seem to converge in the distance. The same is true for two physically parallel rows of light points observed in the dark room. In the Hillebrand experiment the rows of light points are arranged so that they no longer converge but seem to form a parallel "alley". The resulting divergent physical curves have a characteristic form comparable to that of hyperbolas.

(e) Hillebrand's experiment was repeated by Blumenfeld[3] under improved technical conditions. The general result was the same but an additional observation was made. When the observer was instructed to pay predominant attention to the distance between opposite points, and, by making them equal, to set up alleys of apparently equidistant walls, the resulting curves had the general form found by Hillebrand, but did not appear parallel and straight. The "distance alleys" differed from the "parallel alleys"and were found to lie consistently outside the parallel alleys (Fig. 4).

4. THE PSYCHOMETRIC DISTANCE FUNCTION

The preceding experiments indicate strongly that the visual space, as revealed in dark room experiments, can be characterized mathematically as a metric space. This means that we may assume the existence of a dis-

[2] F. Hillebrand, Denkschr. Akad. Wiss. Wien, math.-nat. Kl. 72, 255 (1902).

[3] W. Blumenfeld, Zeits. f. Physiol. d. Sinnesorgane 65, 241 (1913).

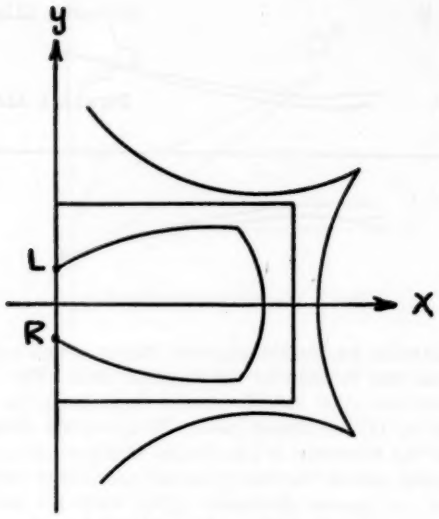

FIG. 5. Equivalent configurations.

tance function, $D(P_1, P_2)$, which accounts quantitatively for the observations just described. In other words, we assume that to any two points P_1, P_2 of the visual space, a non-negative number can be assigned which measures the sensed distance, (P_1P_2), between these two points.

Any such distance function must satisfy the following conditions:

(1) $D(P_1, P_2)=D(P_2, P_1)>0$, if P_1, P_2 are sensed as different.
(2) $D(P_1, P_2)=0$ if $P_1=P_2$. (4.1)
(3) $D(P_1, P_2)+D(P_2, P_3)\geqq D(P_1, P_3)$ for any 3 points P_1, P_2, P_3.

The physical distance $D^*(P_1^*, P_2^*)$ though it obviously satisfies the condition (4.1) cannot be considered as a distance function of the corresponding sensations because it would not measure the sensed distance correctly. In fact, we have already seen that it would not satisfy the following further condition which must be fulfilled by the distance function:

(1) If (P_1, P_2) and (P_3, P_4) are any two pairs of sensed points and $(P_1, P_2)>(P_3, P_4)$ then $D(P_1, P_2)>D(P_3, P_4)$. (4.2)
(2) If P_1, P_2, P_3 are sensed on an apparently straight line, then $D(P_1, P_2)+D(P_2, P_3)=D(P_1, P_3)$ and vice versa.

A distance function $D(P_1, P_2)$ which satisfies both conditions (4.1) and (4.2) is called a *psychometric distance function*. Our problem is to determine this function for the visual space, and, if possible, to express it in terms of the physical coordinates of the stimulating points P_1^*, P_2^*.

5. THE INDETERMINACY OF THE DISTANCE FUNCTION

First we ask whether such a function is uniquely determined by the preceding conditions. For if a multiplicity of possible distance functions existed, any one of them would give us merely an empirical description of certain experimental findings. But if the function is uniquely determined, the establishment of its explicit form must represent an interesting psychological result concerning the nature of visual sensations.

Obviously, D is not uniquely determined since along with $D(P_1, P_2)$ any other function $\bar{D}(P_1, P_2)=C\cdot D(P_1, P_2)$, C being a positive constant, satisfies the conditions. It can be shown, however, that this indeterminacy is the only one possible.

In order to show this mathematically, we formulate certain basic assumptions which are concerned with the *compactness* and the *convexity* of the visual space.

(a) *The visual space is finitely compact:* To any infinite sequence P_ν such that $D(P_1, P_\nu)$ is bounded, there exists a subsequence P_{n_ν} and a point P of the visual space such that $D(P_{n_\nu}, P)\to 0$.

(b) *The visual space is internally convex:* To any pair of points P_1, $P_2 (P_1\neq P_2)$ there exists a third point Q such that $D(P_1, Q)+D(Q, P_2)=D(P_1, P_2)$.

General postulates of this nature, of course, cannot be tested by experiments since an infinity of points is involved. Yet, they are not arbitrary assumptions but formulations of certain observations which we make with regard to our own visual sensations.

The uniqueness of the psychometric distance function can now be readily deduced. Suppose there are two such functions $D(P_1, P_2)$ and $\bar{D}(P_1, P_2)$, both satisfying all requirements. Then, whenever $(P_1P_2)>(P_3P_4)$ then $D(P_1, P_2)>D(P_3, P_4)$ and $\bar{D}(P_1, P_2)>\bar{D}(P_3, P_4)$. It follows that $\bar{D}(P_1, P_2)>\bar{D}(P_3, P_4)$ whenever $D(P_1, P_2)>D(P_3, P_4)$. This is possible only if $\bar{D}=f(D)$, for all points where D and $\bar{D}$ are defined. Consider next any two points P_1, P_2 of the visual space and assume that $D(P_1, P_2)=a>0$. As a consequence of compactness and internal convexity, it can be shown that to any number t of the interval $0\leqq t\leqq a$ there exists a point Q such that $D(P_1, Q)=t$ and $D(Q, P_2)=a-t$. On account of the straight line condition (4.2) it follows that $\bar{D}(P_1, Q)+\bar{D}(Q, P_2)=\bar{D}(P_1, P_2)$, or $f(t)+f(a-t)=f(a)$ for any t in $0\leqq t\leqq a$ and for any a determined by a pair of points P_1, P_2. This leads to the conclusion $f(t)=Ct$ and hence $\bar{D}(P_1, P_2)=C\cdot D(P_1, P_2)$, where C is a constant.

Thus, the only possible indeterminacy of the psychometric distance function is a multiplicative constant. This means that the ratio $D(P_1, P_2)/D(P_3, P_4)$ of two distances is a uniquely determined function of the four points in question. This result is in agreement with the observation made previously that the inequality sign in the sensation $(P_1P_2)>(P_3P_4)$ is determined by the physical coordinates of the points P_1^*, P_2^*, P_3^*, P_4^*. We conclude that the ratio $D(P_1, P_2)/D(P_3, P_4)$ will be a function of the physical coordinates of the four stimu-

lating points which is invariant for an individual observer. It establishes a constant relationship between the objective physical space and the subjective visual space of the observer which is unaffected by other psychological factors. Any parameters in this relation, which are not the physical coordinates of the four points, must be constant factors of the personality of the observer, characterizing his visual reaction to external nature.

6. THE FORM OF THE DISTANCE FUNCTION

In order to find an explicit expression for the psychometric function $D(P_1, P_2)$, we make use of certain general psychological observations and of certain instructive experiments. These observations are concerned with the thesis that there is no absolute localization even in binocular vision. A given physical configuration provides no immediate visual clues which could determine localization and absolute phenomenological size of the sensed configuration. Localization and size are determined by other non-visual psychological factors, in particular, by the intellectual experience of the observer.

Depending upon such factors, the same physical configuration may be seen in different localizations and different phenomenological sizes. Vice versa, entirely different physical configurations may give rise to the same visual sensation.

This principle is readily seen to apply to monocular vision, in fact, this is the tacit assumption in reproducing a visual sensation by painting. Its validity in binocular vision is indicated by observations of an isolated point. But there are more convincing demonstrations.

Ames of the Dartmouth Eye Institute has shown that to a given ordinary rectangular room, a set of distorted rooms can be constructed, which, if viewed from a fixed position, are indistinguishable from the original room (Fig. 5). In fact, the illusion of seeing the original room in all cases is inescapable if suitable suggestive details, for example, window frames, are included. Obviously, it is our experience of living in rectangular rooms which causes us to see the rectangular form even though the physical reality is quite different. The distorted rooms, of course, cannot be constructed arbitrarily. Certain metric clues must be identical in all of them.

In order to combine this principle of the lack of absolute localization with our previous result concerning the existence of a psychometric distance function we are forced to the conclusion that $D(P_1, P_2)$ must be a distance function of a homogeneous metric space, that is, a Riemannian space of constant curvature. For only in these spaces form and localization are completely uncorrelated, which means that the form of a configuration provides no clues for its localization.

The preceding considerations warrant the introduction of the hypothesis of constant curvature, but there is another observation which adds strong support to the hypothesis. Observations in the dark room reveal that we not only have an immediate sensation of straightness but also of plane surfaces. If light points or pliable wires are arranged in apparently plane surfaces, the resulting physical surfaces are curved. If any two points of a "visual plane" are connected by a visually straight line, it would not leave the visual plane. It is well known that two arbitrarily located dimensional submanifolds of this type exist only in the homogeneous spaces. Thus, the very existence of an immediate sensation of "planeness" can be considered as additional evidence in favor of the hypothesis of constant curvature.

The mathematical consequence of this hypothesis is that there exists in the visual space a subjective coordinate system, such that the psychometric distance function $D(P_1, P_2)$ is given by the formula:

$$\frac{2}{(-K)^{\frac{1}{2}}}\sin\left[\frac{1}{2}(-K)^{\frac{1}{2}}\cdot\frac{D}{C}\right] = \frac{[(\xi_1-\xi_2)^2+(\eta_1-\eta_2)^2+(\zeta_1-\zeta_2)^2]^{\frac{1}{2}}}{\left[\left(1+\frac{K}{4}\rho_1^2\right)\left(1+\frac{K}{4}\rho_2^2\right)\right]^{\frac{1}{2}}} \tag{6.1}$$

where $\rho_n^2=\xi_n^2+\eta_n^2+\zeta_n^2$, and K and C are real valued constants which are as yet undetermined. We interpret ξ, η, ζ as cartesian coordinates in a Euclidean space. Thus we obtain a Euclidean map of the visual space, which, in general, is not isometric, since the distance of two points is given by a distance function (6.1) which is non Euclidean if $K\neq 0$.

The question whether the geometry of the visual space is elliptic, hyperbolic or Euclidean, i.e. whether in (6.1) $K>0$, $K<0$ or $K=0$ can only be answered by

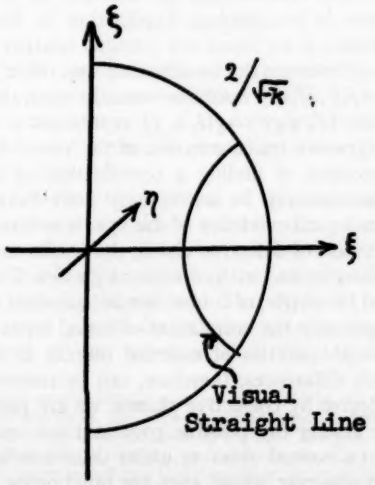

FIG. 6. A visually straight line represented in hyperbolic space.

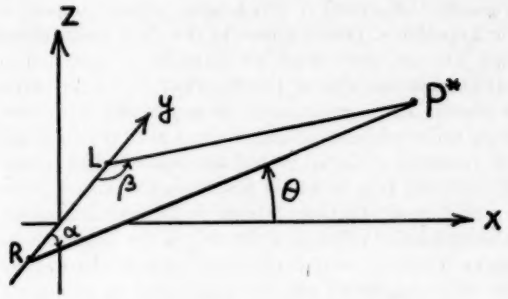

FIG. 7. Bipolar coordinates of a physical point.

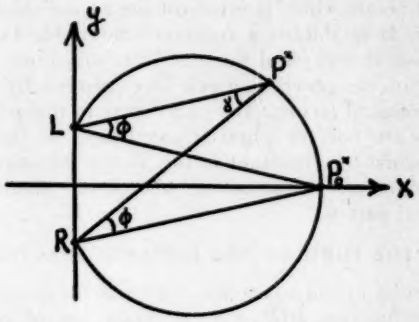

FIG. 8. Bipolar parallax and bipolar latitude of a physical point.

experiments. All experiments carried out thus far indicate that K is negative, which means that the visual space must be a part of a hyperbolic or Lobachevski space.

The total hyperbolic space is represented in our map by the interior of the sphere $\xi^2+\eta^2+\zeta^2=-4/K$. The visual straight lines are given by circles which intersect the basic sphere at right angles; all of these geodesics are thus represented by plane curves which lie in the planes through the origin (Fig. 6).

The visual planes are represented by spheres which intersect the basic sphere at right angles.

Because of the symmetry of the metric (6.1) with regard to the origin, we identify the origin $\xi=\eta=\zeta=0$ with the apparent center of observation in the visual space. Furthermore we coordinate the ξ, η-plane to the subjective horizontal plane, the ξ, ζ-plane to the median plane, and the η, ζ-plane to the frontal plane.

7. RELATION OF VISUAL TO PHYSICAL SPACE

Next we establish a relation of the subjective coordinates ξ, η, ζ of a sensed point P to the physical coordinates of its stimulating point P^*. As stated before, no such relation can be constant or necessary since there is no absolute localization in the visual space. Hence, if we found one possible relation $(x, y, z)=f(\xi, \eta, \zeta)$ between the coordinates, any other relation $(x, y, z)=f(\xi', \eta', \zeta')$ would be visually equivalent provided that $(\xi', \eta', \zeta')=g(\xi, \eta, \zeta)$ represents a motion, i.e. a congruence transformation of the visual space.

The problem of finding a coordination of the two spaces can actually be solved only individually since the physiological condition of the eyes is a determining factor. In case of defective vision, the results are different for observations with or without glasses. The visual space and its metric, of course, are independent of these conditions; only the correlation of visual sensations to the physical qualities of external objects is affected. Since such differences, therefore, can be removed to a certain degree by corrective glasses, we are justified in choosing among the possible coordinations one which applies to a normal observer under usual conditions.

For an observer whose eyes are functioning equally well, we may assume that objects in the physical x, y-plane are seen in the subjective horizontal ξ, η-plane, and also, that points in the x, z-plane are placed into the median ξ, ζ-plane. For the further description of the required relationship we introduce, in the physical space, a special bipolar system of angular coordinates which is better adapted to the physiological mechanism of binocular vision. Consider the plane through a point P^* and through the eyes R and L. Its angle θ with the x, y-plane is called the *angle of elevation*. In this plane of elevation, two lines are drawn from R and L toward P^*. These lines determine the positions of the optical axes of the eyes if the point P^* is fixated. We characterize these lines by their angles α and β with the y axis as shown in Fig. 7. The localization of the point P^* is then determined by the three angles α, β, θ. Instead of α and β we shall use the linear combinations:

$$\begin{aligned}\gamma&=\pi-\alpha-\beta\\ \phi&=\tfrac{1}{2}(\beta-\alpha)\end{aligned}\qquad(7.1)$$

which are called the *bipolar parallax* and the *bipolar latitude* of a point P^* (Fig. 8). In any plane of elevation, the curves $\gamma=$ const. are circles through the eyes, the so-called Vieth-Mueller circles, whereas the curves $\phi=$ const. are hyperbolas, the Hillebrand hyperbolas, whose asymptotes go through the point $x=y=z=0$ (Fig. 9).

If a Vieth-Mueller circle is rotated about the y axis, a torus surface $\gamma=$ const. is obtained which shall be called a *Vieth-Mueller torus*.

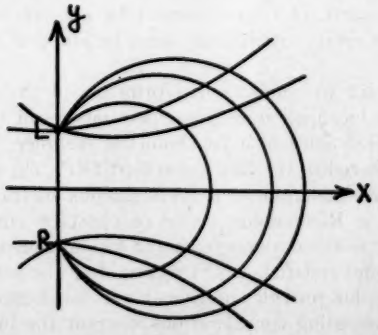

FIG. 9. Curves of constant bipolar parallax and latitude.

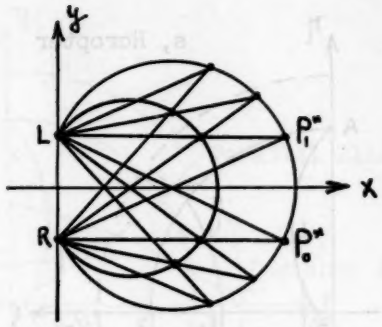

FIG. 10. Testing correlation between physical and visual spaces on Vieth-Mueller circle by changing convergence.

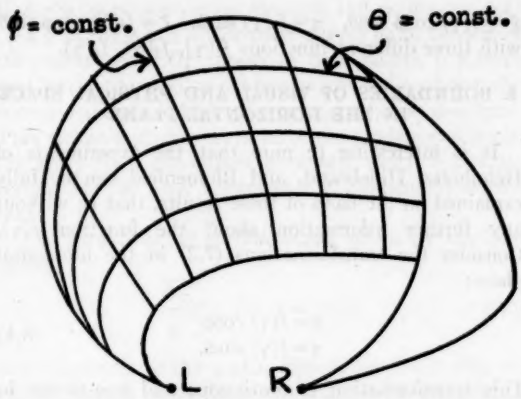

FIG. 11. Torus of constant binocular parallax, showing curves of constant elevation and constant binocular latitude.

For infinitely distant points of the physical space, we have $\gamma=0$. Since these points give the visual impression of forming an apparently spherical dome of finite radius around the observer,‡ we represent them, in the ξ, η, ζ-space, as points on a sphere concentric to the origin. This sphere will include the total visual part of the visual space. We choose arbitrarily *a sphere of radius 2 to represent physical infinity.*

This normation makes the constant K in the expression (6.1) for $D(P_1, P_2)$ a dimensionless parameter, with individual differences in K indicating differences in visual perception.

Since we have no visual sensations of infinite size, we conclude that K can never be smaller than -1, so that the basic sphere, $2/(-K)^{\frac{1}{2}}$, in case $K\leqq 0$, lies always outside the sphere of radius 2 which represents physical infinity. The two spheres coincide if $K=-1$; in which case astronomical objects would give an immediate sensation of immense size and distance. Though this limiting case is never reached, we conclude that visual sensation of size and distance relations agrees with physical reality better the nearer the value of K is to -1. Thus, individual differences in the parameter K may correlate with individual differences in certain mechanical skills.

Further indication of the correlation of the ξ, η, ζ-space to the physical space is obtained by the following observation. We arrange a number of equidistant light points on a Vieth-Mueller circle, as shown in Fig. 10. These points are seen in the visual space as equidistant points on a circle about the center of observation. If the distance between the points P_0^*, P_1^* is made equal to the interpupillary distance of the eyes, the configuration can be "projected" toward infinity ($\gamma=0$) by simply diverging the eyes to a position of parallel optical axes. By overconverging, the configuration may be projected on smaller Vieth-Mueller circles (Fig. 10). In this way we can conveniently verify the original observation for a set of such circles. If the point configuration is rotated about the y axis, and arrested at a number of equidistant θ positions, a set of points is obtained which lie on certain curves $\phi=$ const. and $\theta=$ const. of the Vieth-Mueller torus $\gamma=$ const. Wires placed along these curves would form a network like that shown in Fig. 11. If this is observed from the points R and L, the resulting sensation is approximately that of meridians and circles of latitude on a sphere around the observer. This means that the torus surfaces $\gamma=$ const. appear as concentric spheres around the center of observation, and the bipolar angles ϕ and θ as polar coordinates in the ξ, η, ζ-space. The observation may be verified for a number of such torus configurations by simply overconverging or diverging the eyes as before. Mathematically, these observations are expressed by the equations:

$$\begin{aligned}\xi&=f(\gamma)\cos\phi\cos\theta\\ \eta&=f(\gamma)\sin\phi\\ \zeta&=f(\gamma)\cos\phi\sin\theta\end{aligned}\qquad(7.2)$$

which relate physical and subjective coordinates. The function $f(\gamma)$ is a non-negative function of γ which increases monotonically if γ decreases from positive values to $\gamma=0$. From the preceding convention it follows that $f(0)=2$.§

Even for the neighborhood of the horizontal plane, this formulation should be considered no more than a first approximation. There is experimental evidence of small Vieth-Mueller circles giving an elliptical rather than a circular impression. Therefore, it is possible that a more precise formulation may require the replacement of the relations (7.2) by the following:

‡ In a more careful investigation, the fact that the sky appears to be a flattened dome could be considered. Thus, the following arguments are to be taken as approximations referring to visual sensation in the neighborhood of the horizontal plane.

§ A more careful experimentation may lead to the result that, at greater distances, the network configuration is not seen as a sphere but as an oval, flattened at the top. The previously mentioned impression of the sky, and also the so-called moon phenomenon, seem to indicate this possibility. In this case, the relation $\zeta=f(\gamma)\cos\phi\sin\theta$ would have to be replaced by a relation $\zeta=f_1(\gamma)\cos\phi\sin\theta$ with $f_1(\gamma)<f(\gamma)$.

$\xi=f_1(\gamma)\cos\phi\cos\theta$, $\eta=f_2(\gamma)\sin\phi$, $\zeta=f_3(\gamma)\cos\phi\sin\theta$, with three different functions $f_1(\gamma)$, $f_2(\gamma)$, $f_3(\gamma)$.

8. BOUNDARIES OF VISUAL AND PHYSICAL SPACE IN THE HORIZONTAL PLANE

It is interesting to note that the experiments of Helmholtz, Hillebrand, and Blumenfeld can be fully explained on the basis of these results, that is, without any further information about the function $f(\gamma)$. Consider the transformations (7.2) in the horizontal plane:

$$\begin{aligned}\xi&=f(\gamma)\cos\phi\\ \eta&=f(\gamma)\sin\phi.\end{aligned}\tag{8.1}$$

This transformation is continuous and one-to-one in the interior of the half-plane $x>0$; it is, however, quite irregular on the boundary (Fig. 12). In fact, the boundary of this half-plane is characterized by the following conditions for the bipolar coordinates γ and ϕ:

$$\begin{aligned}&A\text{: } \gamma=0,\ \phi=\pi/2, && \text{or } x=0,\ y>1\\ &L\text{: } \gamma=\pi-2\phi, && \text{or } x=0,\ y=+1 \text{ (left eye)}\\ &B\text{: } \gamma=\pi,\ \phi=0, && \text{or } x=0,\ -1<y<1\\ &R\text{: } \gamma=\pi+2\phi, && \text{or } x=0,\ y=-1 \text{ (right eye)}\\ &C\text{: } \gamma=0,\ \phi=-\pi/2, && \text{or } x=0,\ y<-1.\end{aligned}\tag{8.2}$$

The Sections A, B, C of the y axis are contracted into three isolated points A: $\xi=0$, $\eta=2$; B: $\xi=f(\pi)$, $\eta=0$, C: $\xi=0$, $\eta=-2$ whereas the two eyes are stretched out into two curves $\rho_1=f(\pi-2\phi)$, $\rho_2=f(\pi+2\phi)$ which connect the point B with A and C respectively. These two curves join at B at an acute angle, as follows from the fact that $f(\gamma)$ increases with decreasing γ, i.e. $f'(\gamma)<0$, and hence $d\rho_1/d\phi>0$, $d\rho_2/d\phi<0$.

The half-plane $x>0$ is thus imaged into a scythe-shaped domain of the ξ, η-plane as shown in Fig. 13. The image of the half-space $x>0$ is obtained by simply rotating this domain around the η-axis.

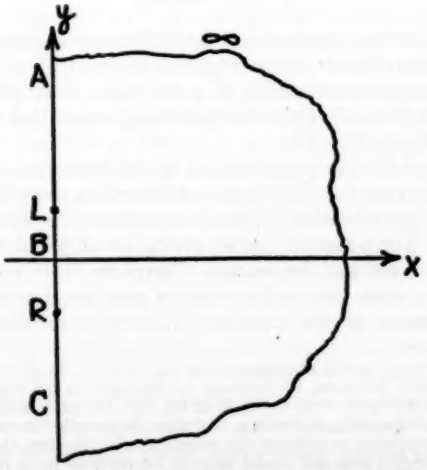

FIG. 12. Boundaries of the horizontal half-plane in physical space.

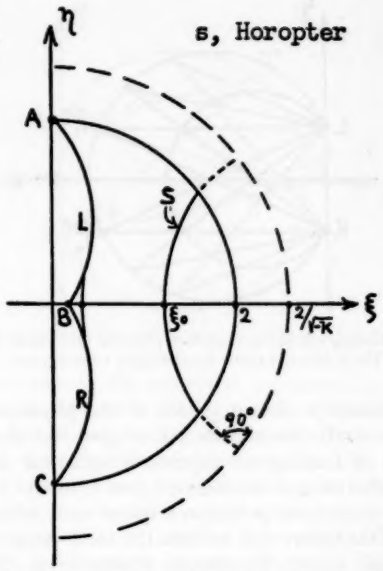

FIG. 13. Boundaries of the horizontal half-plane of visual space and a frontal plane horopter, S, mapped on a ξ,η-diagram.

9. HOROPTERS AND ALLEYS

We interpret Helmholtz' horopter curves as those geodesics of the ξ, η-plane which are symmetric to the ξ axis (Fig. 13). Their equation is:

$$\frac{K}{4}(\xi^2+\eta^2)-1=C\xi.\tag{9.1}$$

If $K<0$, they are circles normal to the basic circle $2/(-K)^{\frac{1}{2}}$ and normal to the ξ axis. Two different groups of circles can be distinguished. Starting from a point ξ_0 of the ξ axis, they either reach directly the circle $\xi^2+\eta^2=4$ representing infinity, or they are intercepted by the curves representing the eyes.

Their counterparts in the physical x, y-plane, therefore, must be curves which, starting from x_0, either go

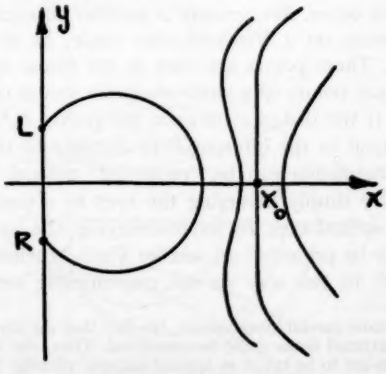

FIG. 14. Frontal plane horopters.

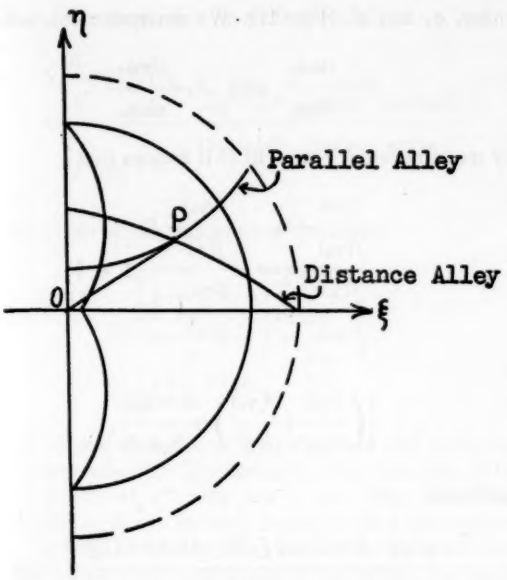

FIG. 15. Distance and parallel alleys in map of subjective horizontal plane.

asymptotically toward infinity or approach the eyes R and L. Thus they are curves of precisely the type observed in the horopter experiment. In particular, there must be one curve, which, in the neighborhood of the x axis, is practically straight (Fig. 14).

This situation not only exists for the case $K<0$, but also for $K=0$ or $K>0$. If $K=0$, the horopter curves (9.1) are straight lines, if $K>0$, they are circles through the points $\eta=\pm 2/(K)^{\frac{1}{2}}$ of the η axis. In either case, as before, the two different groups can be distinguished.

The distance alleys of Blumenfeld are given by the equation:

$$\frac{K}{4}(\xi^2+\eta^2)+1=C\eta. \tag{9.2}$$

If $K<0$, they are circles through the points $\xi=\pm 2/(-K)^{\frac{1}{2}}$ of the ξ axis. Since these curves lie to the left of the radius vector OP to any of their points, it follows that their physical counterparts must lie above the corresponding sections of the hyperbolas $\phi=$const. This means that they must have the tendency of bending away from the curves $\phi=$const. which is characteristic for the alley curves in the Blumenfeld experiment.

The parallel alleys of Hillebrand, given by the geodesics:

$$\frac{K}{4}(\xi^2+\eta^2)-1=-C\eta \tag{9.3}$$

are symmetric to the η axis. Hence, for $K<0$ they are circles normal to the basic circle $2/(-K)^{\frac{1}{2}}$ and normal to the η axis. Also these curves lie above any radius vector OP and thus have the same characteristic form as the distance alleys.

If a parallel alley and a distance alley are started from the same point P, the parallel alley lies inside the distance alley, in agreement with actual observations (Figs. 15 and 16).

If $K=0$, parallel alleys and distance alleys are identical, namely, straight lines $\eta=$const. in the ξ, η-plane. For $K>0$, distance alleys are represented by circles normal to the sphere $\rho=2/(K)^{\frac{1}{2}}$, parallel alleys by circles through the points $2/(K)^{\frac{1}{2}}$ of the ξ axis. In this case, therefore, the distance alley should lie inside the parallel alley. The Blumenfeld experiment contradicts this, thus giving a direct demonstration that the space of binocular vision is a Lobachevski space.

10. USE OF ALLEY DATA TO DETERMINE $f(\gamma)$ AND K

The Hillebrand-Blumenfeld alleys can be used to determine the function $f(\gamma)$ and the constant K. Consider a distance and a parallel curve which starts from the same point:

$$\begin{aligned}\xi_0&=f(\gamma_0)\cos\phi_0\\ \eta_0&=f(\gamma_0)\sin\phi_0.\end{aligned} \tag{10.1}$$

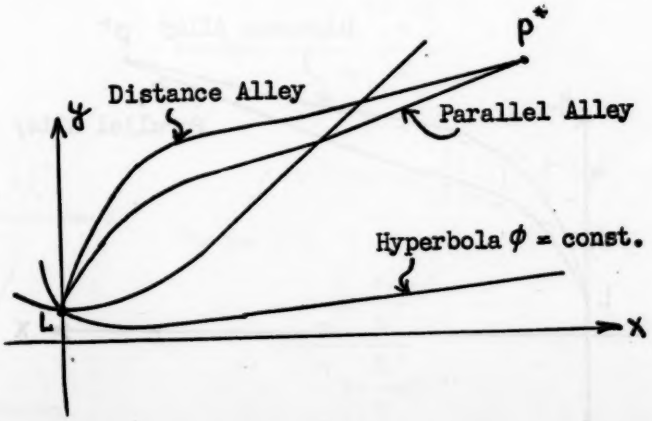

FIG. 16. Distance and parallel alleys in physical horizontal plane.

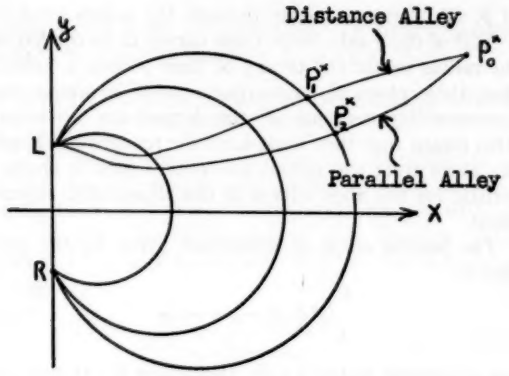

FIG. 17. Distance and parallel alleys with a common point in a system of Vieth-Mueller circles.

From (9.2) and (9.3) it follows that

$$\frac{\frac{K}{4}f^2(\gamma)+1}{f(\gamma)\sin\phi_1}=\frac{\frac{K}{4}f^2(\gamma_0)+1}{f(\gamma_0)\sin\phi_0} \quad \text{(distance curve)}$$

and

$$\frac{\frac{K}{4}f^2(\gamma)-1}{f(\gamma)\sin\phi_2}=\frac{\frac{K}{4}f^2(\gamma_0)-1}{f(\gamma_0)\sin\phi_0} \quad \text{(parallel curve)},$$

or

$$\begin{aligned}\frac{K}{4}f^2(\gamma_0)\left(\frac{f(\gamma)}{f(\gamma_0)}-\frac{\sin\phi_1}{\sin\phi_0}\right)&=-\frac{f(\gamma_0)}{f(\gamma)}+\frac{\sin\phi_1}{\sin\phi_0}\\ \frac{K}{4}f^2(\gamma_0)\left(\frac{f(\gamma)}{f(\gamma_0)}-\frac{\sin\phi_2}{\sin\phi_0}\right)&=-\frac{\sin\phi_2}{\sin\phi_0}+\frac{f(\gamma_0)}{f(\gamma)}.\end{aligned} \tag{10.2}$$

A Vieth-Mueller circle of parallax γ is intersected by the two curves at P_1^* and P_2^* of different bipolar latitudes, ϕ_1 and ϕ_2 (Fig. 17). We determine the ratios

$$S_1=\frac{\sin\phi_1}{\sin\phi_0} \quad \text{and} \quad S_2=\frac{\sin\phi_2}{\sin\phi_0}$$

by measurements. From (10.2) it follows that

$$\frac{\frac{f(\gamma)}{f(\gamma_0)}-S_1}{\frac{f(\gamma)}{f(\gamma_0)}-S_2}=-\frac{\frac{f(\gamma_0)}{f(\gamma)}-S_1}{\frac{f(\gamma_0)}{f(\gamma)}-S_2},$$

or

$$\frac{1}{2}\left(\frac{f(\gamma)}{f(\gamma_0)}+\frac{f(\gamma_0)}{f(\gamma)}\right)=\frac{1+S_1S_2}{S_1+S_2},$$

and hence

$$\frac{f(\gamma_0)}{f(\gamma)}=\frac{1+S_1S_2+[(S_1^2-1)(S_2^2-1)]^{\frac{1}{2}}}{S_1+S_2}. \tag{10.3}$$

Since parallel and distance curves are in general not far apart, we may replace S_1 and S_2 by an intermediate value $\sin\phi/\sin\phi_0=S$. Then it follows from (10.3) that

$$\frac{f(\gamma_0)}{f(\gamma)}\approx S=\frac{\sin\phi}{\sin\phi_0}, \tag{10.4}$$

i.e. the function $\log f(\gamma)$ is obtained directly if a distance or a parallel alley is plotted in the coordinates γ and $\log\sin\phi$.

The experiments seem to indicate that the function $\log f(\gamma)$ in first approximation can be considered as a linear function of γ. Then $\log f(\gamma)=-\sigma\gamma+C$ or $f(\gamma)=2e^{-\sigma\gamma}$, σ being a new parameter of the observer.

The constant $(K/4)f^2(\gamma_0)$ can be found from (10.2) by introducing the expression (10.3) in one of the Eqs.

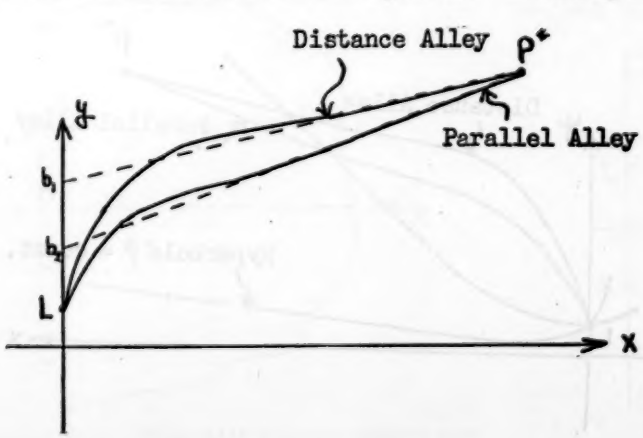

FIG. 18. Tangents to distance and parallel alleys at the common point.

(10.2). The result may be written as follows:

$$\frac{-\frac{K}{4}f^2(\gamma_0)+1}{\frac{K}{4}f^2(\gamma_0)+1}=\frac{(S_1^2-1)^{\frac{1}{2}}}{(S_2^2-1)^{\frac{1}{2}}}=\frac{(\sin^2\phi_1-\sin^2\phi_0)^{\frac{1}{2}}}{(\sin^2\phi_2-\sin^2\phi_0)^{\frac{1}{2}}}.$$

This yields at the end point of the alleys

$$\left[\frac{1-\frac{K}{4}f^2(\gamma_0)}{1+\frac{K}{4}f^2(\gamma_0)}\right]^2=\frac{\frac{d\phi_1}{d\gamma}}{\frac{d\phi_2}{d\gamma}}=\frac{b_1}{b_2}.$$

It is readily shown that $2(d\phi_1/d\gamma)=b_1$ and $2(d\phi_2/d\gamma)=b_2$ determine the intersection of the tangents of the two curves at P^* with the y axis (Fig. 18). Thus, the ratio b_1/b_2 can be used directly to find the constant $(K/4)f^2(\gamma_0)$. If the two alleys start at the same infinitely distant point, we have $f(\gamma_0)=2$, and hence the simple relation

$$\left(\frac{1-K}{1+K}\right)^2=\frac{b_1}{b_2}.$$

11. METHODS OF MEASURING K AND $f(\gamma)$

The alley experiments provide a convincing demonstration of the non-Euclidean hyperbolic character of the binocular visual space. But they are not too well suited for the problem of measuring the parameters of the metric. The mechanical construction has to be quite elaborate, if undesirable clues are to be eliminated that would invalidate the measurements. The setting up of a pair of alleys requires time, especially with new observers. Consistency is generally lacking at the beginning so that each new observer must go through a series of preparatory experiments.

In order to remove these difficulties, other methods

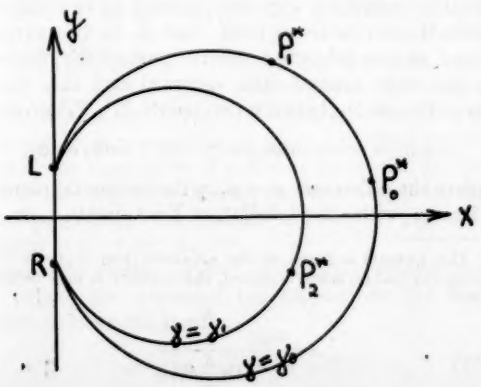

FIG. 19. Points on two Vieth-Mueller circles.

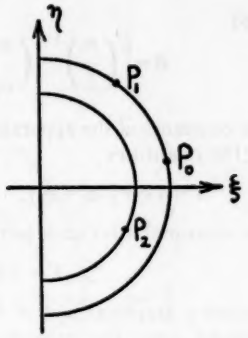

FIG. 20. The subjective correlation of Fig. 19.

of measurement had to be investigated. The following method so far seems to promise the best results.

Three isolated light points P_0^*, P_1^*, P_2^* are given in the horizontal plane. P_0^* and P_1^* are movable on a fixed Vieth-Mueller circle of parallax γ_0, P_2^* on a second fixed Vieth-Mueller circle of parallax γ_1 (Fig. 19).

In the ξ, η-plane, these points are represented by the two points P_0 and P_1 on a circle of radius $\rho_0=f(\gamma_0)$, and by a third point P_2 on a circle $\rho_1=f(\gamma_1)$ (Fig. 20). Both circles are concentric to the origin. The task of the observer is to set the point P_2^* in such a position on its circle that the visual distance $D(P_0P_2)$ is equal to the visual distance $D(P_0P_1)$. This is carried out for a number of settings P_0^*, P_1^* on the Vieth-Mueller circle γ_0. From (6.1) it follows that the distances are equal if

$$\frac{\{2\rho_0^2[1-\cos(\phi_1-\phi_0)]\}^{\frac{1}{2}}}{1+\frac{K}{4}\rho_0^2}=\frac{[\rho_0^2+\rho_1^2-2\rho_0\rho_1\cos(\phi_2-\phi_1)]^{\frac{1}{2}}}{\left(1+\frac{K}{4}\rho_0^2\right)^{\frac{1}{2}}\left(1+\frac{K}{4}\rho_1^2\right)^{\frac{1}{2}}}, \quad (11.1)$$

i.e. if

$$4\sin^2\tfrac{1}{2}(\phi_2-\phi_0)=\frac{\rho_0}{\rho_1}\frac{1+\frac{K}{4}\rho_1^2}{1+\frac{K}{4}\rho_0^2}\times 4\sin^2\tfrac{1}{2}(\phi_1-\phi_0)-\left[\left(\frac{\rho_0}{\rho_1}\right)^{\frac{1}{2}}-\left(\frac{\rho_1}{\rho_0}\right)^{\frac{1}{2}}\right]^2. \quad (11.2)$$

The quantities

$$A=\frac{\rho_0}{\rho_1}\frac{1+\frac{K}{4}\rho_1^2}{1+\frac{K}{4}\rho_0^2}$$

and

$$B=\left[\left(\frac{\rho_0}{\rho_1}\right)^{\frac{1}{2}}-\left(\frac{\rho_1}{\rho_0}\right)^{\frac{1}{2}}\right]^2=\frac{\rho_0}{\rho_1}+\frac{\rho_1}{\rho_0}-2 \qquad (11.3)$$

are constants of the apparatus and of the observer.

The quantities

$$X=4\sin^2\tfrac{1}{2}(\phi_1-\phi_0);\quad Y=4\sin^2\tfrac{1}{2}(\phi_2-\phi_0) \qquad (11.4)$$

are measured after each setting. It follows that

$$Y=AX-B, \qquad (11.5)$$

so that a graphical plot of Y against X should yield a straight line. The experimental points are actually found scattered about a certain average straight line. The scattering may be considerable for a new observer, but it decreases rapidly with some training. It is interesting to note that young children display a remarkable degree of certainty and consistency in such observations.

From a suitable number of observations we obtain by the method of least squares the best straight line representation of the observation, and from the constant B the ratio

$$\frac{\rho_1}{\rho_0}=\frac{f(\gamma_1)}{f(\gamma_0)},$$

and from A the quantity $K\cdot f^2(\gamma_0)$.

Repetition of these experiments with other pairs of Vieth-Mueller circles yields further ratios $f(\gamma_{i+1})/f(\gamma_i)$, and thus, with $f(0)=2$, a numerical tabulation of $f(\gamma)$ is obtained. Measurements such as these, as well as other observations, seem to indicate that a first approximation of the ratio $f(\gamma_1)/f(\gamma_0)$ depends only on the difference $\gamma_1-\gamma_0$. This implies that $\log f(\gamma)$ is a linear function of γ, and hence

$$f(\gamma)=2e^{-\sigma\gamma}, \qquad (11.6)$$

where σ is an individual constant of the observer.

The numerical value of σ characterizes the degree of depth perception of a person. There is no doubt that considerable differences exist in the quality of depth perception; σ-values ranging from 4 to 15 have been found.

The parameter σ can be determined from observations on a single pair of Vieth-Mueller circles. We have $2\sinh(\sigma/2)(\gamma_1-\gamma_0)=(B)^{\frac{1}{2}}$, and hence, in sufficient approximation

$$\sigma=\frac{(B)^{\frac{1}{2}}}{\gamma_1-\gamma_0}. \qquad (11.7)$$

If σ is known, the constant A can be utilized to calculate K. However, if the two Vieth-Mueller circles are not far apart, the variation of A with respect to K is not sufficient to provide a good measurement of this constant. A more effective arrangement is the following:

Consider four points P_0^*, P_1^*, P_2^*, P_3^*. The first pair is movable on a Vieth-Mueller circle γ_0, the second pair on a smaller circle of parallax $\gamma_1>\gamma_0$. The task of the observer is to place the point P_3^*, for a given setting of P_0^*, P_1^*, P_2^* so that

$$D(P_0, P_1)=D(P_2, P_3).$$

This leads to the condition

$$2\sin\tfrac{1}{2}(\phi_3-\phi_2)=\frac{\rho_0}{\rho_1}\,\frac{1+\frac{K}{4}\rho_1^2}{1+\frac{K}{4}\rho_0^2}\,2\sin\tfrac{1}{2}(\phi_1-\phi_0) \qquad (11.8)$$

or

$$Y=AX$$

where

$$X=2\sin\tfrac{1}{2}(\phi_1-\phi_0)\quad\text{and}\quad Y=2\sin\tfrac{1}{2}(\phi_3-\phi_2).$$

A graphical plot of the observed quantities Y against the settings X should yield a straight line through the origin. If the two Vieth-Mueller circles are chosen far enough apart, the direction A of this straight line varies considerably with K. Hence, if σ is known, we find K from the relation*

$$A=e^{\sigma(\gamma_1-\gamma_0)}\cdot\frac{1+Ke^{-2\sigma\gamma_1}}{1+Ke^{-2\sigma\gamma_0}}. \qquad (11.9)$$

12. THE HOMOGENEITY OF VISUAL SPACE

The essential feature of the preceding experiments is that distance observations are made on sets of points that are confined to two fixed Vieth-Mueller circles, that is, to curves which are sensed as two subjective circles around the observer. A consequence of this restriction is that certain simple trigonometric functions of the observed angular differences become linear functions of each other, thus providing an elegant method of statistical evaluation. This applies even if the points do not lie in the horizontal plane or the same plane of elevation, provided they are confined to two different Vieth-Mueller torus surfaces, that is, to two surfaces sensed as two subjective spheres around the observer. In this more general case, spherical arcs Ω_{ik}, for instance the arc Ω_{12} between two points P_1^*, P_2^* given by

$$\cos\Omega_{12}=\cos\phi_1\cos\phi_2\cos(\theta_2-\theta_1)+\sin\phi_1\sin\phi_2,$$

replace the differences $\phi_k-\phi_i$ in the horizontal plane.

Hence, with $X=4\sin^2\tfrac{1}{2}\Omega_{01}$; $Y=4\sin^2\tfrac{1}{2}\Omega_{02}$, in the

* This formula is based on the approximation $f(\gamma)=2e^{-\sigma\gamma}$. If this approximation is not accepted, the quantity K may be found from

$$A=\frac{f(\gamma_0)}{f(\gamma_1)}\,\frac{1+\frac{K}{4}f^2(\gamma_1)}{1+\frac{K}{4}f^2(\gamma_0)},$$

if $f(\gamma)$ is known from observations of the first type.

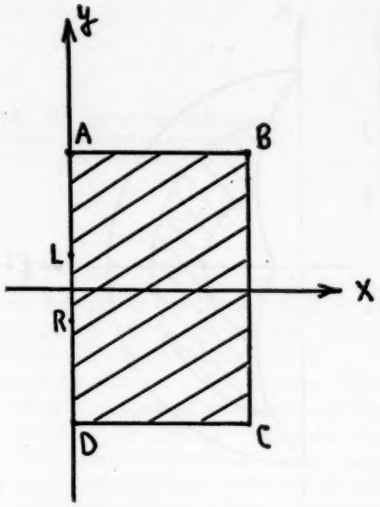

FIG. 21. Horizontal cross-section of Ames' experimental room.

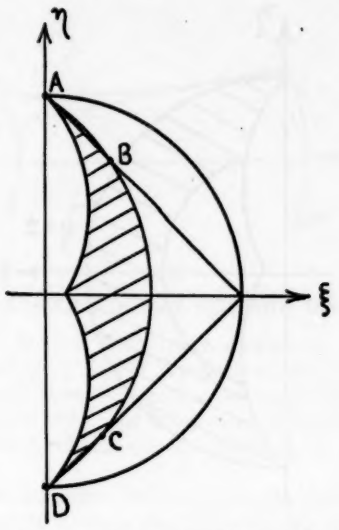

FIG. 22. Rectangle of Fig. 21 mapped in the subjective plane.

experiment of the first type, we should still get points X, Y scattered about the same straight line $Y=AX-B$.

And with $X=2\sin\frac{1}{2}\Omega_{01}$; $Y=2\sin\frac{1}{2}\Omega_{23}$, we should find points about $Y=AX$ in the second experiment. This follows from the special form of the distance function $D(P_0, P_1)$:

$$\frac{2}{(-K)^{\frac{1}{2}}}\sin\left[\frac{1}{2}(-K)^{\frac{1}{2}}\cdot\frac{D}{C}\right] = \frac{(\rho_0^2+\rho_1^2-2\rho_0\rho_1\cos\Omega_{01})^{\frac{1}{2}}}{\left(1+\frac{K}{4}\rho_0^2\right)^{\frac{1}{2}}\left(1+\frac{K}{4}\rho_1^2\right)^{\frac{1}{2}}}. \quad (12.1)$$

More generally, this is true for any metric space whose distance function $D(P_0, P_1)$ has the form

$$D(P_0, P_1)=F[M(\rho_0, \rho_1)+N(\rho_0, \rho_1)\cos\Omega_{01}] \quad (12.2)$$

where $M(\rho_0, \rho_1)$ and $N(\rho_0, \rho_1)$ are symmetric functions of ρ_0 and ρ_1.

Since the linearity of the graphical representation is one of the most consistent observations in these experiments, the question may be considered whether this fact should be interpreted as an experimental verification of the hypothesis of constant curvature. In other words: Are the homogeneous spaces the only Riemannian spaces where the distance function $D(P, Q)$ can be written in the form (12.2)?

Since the metric, defined by (12.2), is symmetric to the origin, the associated line element ds^2 can be assumed to have the form

$$ds^2=n^2(\rho)(d\xi^2+d\eta^2+d\zeta^2) \quad (12.3)$$

so that the distance function $D(\xi_0, \eta_0, \zeta_0; \xi, \eta, \zeta)$ must be a solution of the partial differential equations

$$\begin{aligned} D_\xi^2+D_\eta^2+D_\zeta^2 &= n^2(\rho) \\ D_{\xi_0}^2+D_{\eta_0}^2+D_{\zeta_0}^2 &= n^2(\rho_0). \end{aligned} \quad (12.4)$$

The problem is therefore to determine those functions $n^2(\rho)$ for which the differential equations admit solutions of the special form (12.2).

The answer is that this is possible then, and only then, if $n(\rho)$ has the form

$$n(\rho)=\frac{C}{1+\frac{K}{4}\rho^2} \quad (12.5)$$

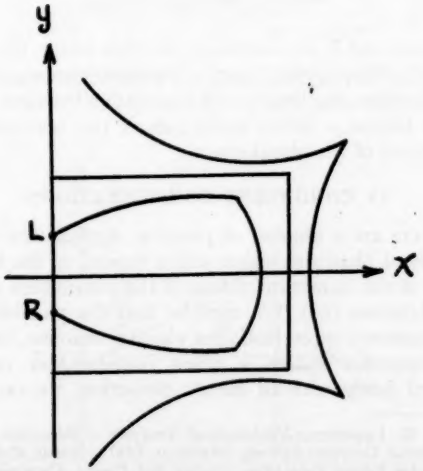

FIG. 23. Horizontal cross sections of visually congruent rooms.

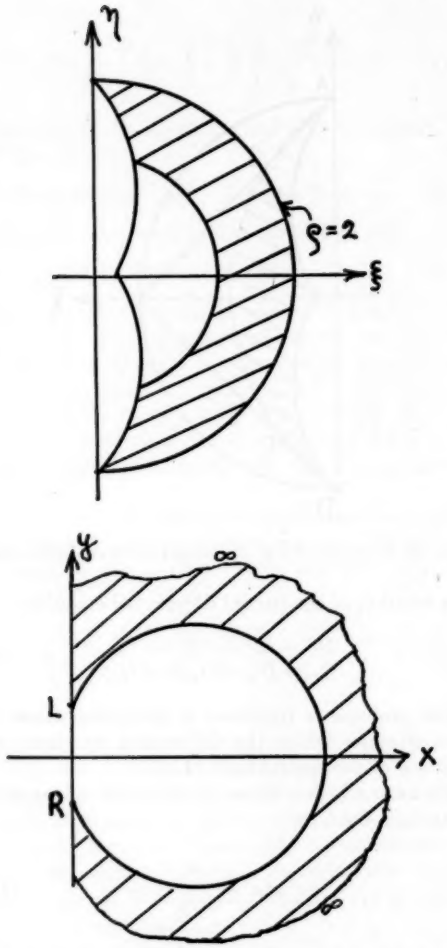

FIG. 24. A domain in the physical plane and the correlated domain in the subjective plane.

where C and K are constants. In other words, the space must be Riemannian space of constant curvature.

Therefore, the linearity of the relation between X and Y is indeed a direct indication of the homogeneous character of the visual space.

13. CONGRUENT CONFIGURATIONS[4]

There are a number of practical applications of the theory of binocular vision which depend on the knowledge of the numerical values of the parameters K and the function $f(\gamma)$. We consider first the possibility of psychometric reproduction of visual sensations. Since in homogeneous spaces a given configuration can be moved freely without metric distortion, we can construct, to any given configuration, a metrically congruent one in any localization or orientation.

[4] R. K. Luneburg, *Mathematical Analysis of Binocular Vision* (Princeton University Press, Princeton, 1947); *Metric Methods in Binocular Visual Perception, Studies and Essays*, Courant Anniversary Volume (Interscience Publishers, Inc., New York, 1948).

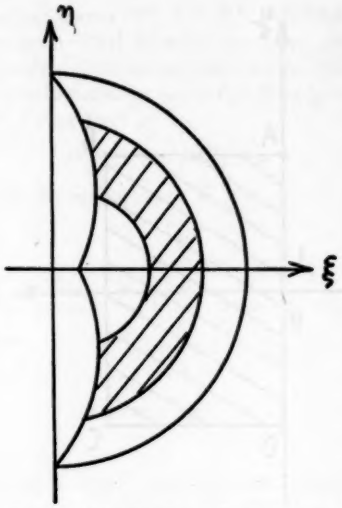

FIG. 25. The domain of Fig. 24 after a congruency-transformation.

The original rectangular room in the Ames experiment may serve as an example. The cross section made with the horizontal plane is shown in Fig. 21, its counterpart in the ξ, η-plane in Fig. 22.

Consider the following hyperbolic motion:

$$\xi' = -a - \left(a^2 + \frac{4}{K}\right)\frac{\xi - a}{(\xi-a)^2+\eta^2+\zeta^2}$$

$$\eta' = \left(a^2 + \frac{4}{K}\right)\frac{\eta}{(\xi-a)^2+\eta^2+\zeta^2} \qquad (13.1)$$

$$\zeta' = \left(a^2 + \frac{4}{K}\right)\frac{\zeta}{(\xi-a)^2+\eta^2+\zeta^2},$$

which transforms median and horizontal planes into

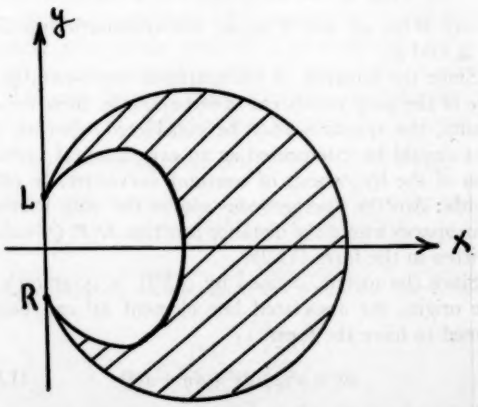

FIG. 26. The domain of Fig. 25 in the physical plane.

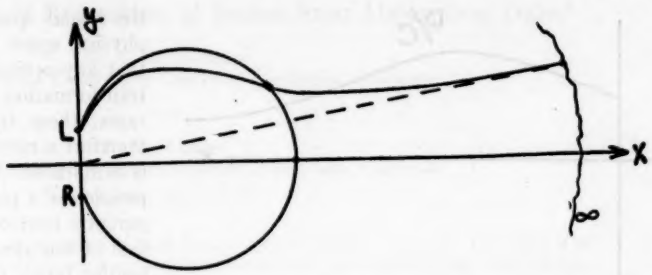

FIG. 27. Illustrating difference between psychometric representation and central projection.

themselves. Submitting the "room" A, B, C, D to this transformation, we find that all the points of the boundary move either to the right or to the left, depending on the parameter a. The physical counterparts of these visually congruent rooms are no longer rectangular but have the form shown in Fig. 23. They conform with Ames' experimental result, and can be used as a quantitative basis for the design of such rooms.

Next, we consider the problem of psychometric reproduction of landscapes, for example, a scenery which lies between a certain Vieth-Mueller circle γ and physical infinity $\gamma=0$. The corresponding domain in the ξ, η, ζ-space lies between two concentric spheres, $\rho=\rho(\gamma)$ and $\rho=2$ (Fig. 24). Submitting this domain to a transformation (13.1) $[a>2/(-K)^{\frac{1}{2}}]$, we obtain a domain bounded by two non-concentric spheres as shown in Fig. 25.

The corresponding domain in the physical space is obtained by rotating the shaded area in Fig. 26 about the y axis. The entire original part of the space is condensed into this narrow shell. With the aid of (13.1) a relief reproduction of the original scenery could be constructed which is visually indistinguishable from the original.‖

If the inner boundary $\rho=\rho(\gamma)$ is sufficiently far away, the relief becomes so flat that it may be replaced by a painting or projected image on the outer screen surface, which is metrically congruent to infinity. In order to find the coordination of a point on this screen, we can use the Blumenfeld alleys since points on these alleys have a constant visual distance from the x axis. If the screen is chosen so small that it lies in the domain where the distance alleys bend away from their asymptotes, the image points depart considerably from the position of central projection (Fig. 27). This explains why the main feature of a landscape appears often disappointingly small compared with the original impression. Therefore in order to obtain a true psychometric projection of a scenery, we should project upon a curved screen designed in accordance with explicit mathematical principles. Furthermore, we should use a projection lens which possesses a strong amount of specified pincushion distortion.

‖ This illusion can be accomplished to a remarkable degree, as for instance the so-called Habitual groups of animal life in the Los Angeles County Museum demonstrate. As a matter of fact, it is nearly impossible to judge the actual dimensions of the scenery.

14. PHENOMENOLOGICAL SIZE AND DISTANCE

Our last result is related to a well-known fact. The phenomenological size of physical objects which are moving away from us, does not decrease in proportion to the angle of view. The size seems to remain constant for a while until, at greater distances, it decreases rapidly.

Consider two points P_0^* and P_1^* in the median plane and symmetric to the x axis (Fig. 28). We judge their apparent distance D according to the formula:

$$\frac{2}{(-K)^{\frac{1}{2}}}\sin\left[\frac{1}{2}(-K)^{\frac{1}{2}}\cdot\frac{D}{C}\right]=\frac{[2\rho^2(1-\cos 2\theta)]^{\frac{1}{2}}}{1+\frac{K}{4}\rho^2}=\frac{2\rho\sin\theta}{1+\frac{K}{4}\rho^2}. \tag{14.1}$$

Since

$$\sin\theta=\frac{z}{(x^2+z^2)^{\frac{1}{2}}}=z\tan\frac{\gamma}{2};$$

and $\rho=2e^{-\sigma\gamma}$, it follows that

$$\frac{2}{(-K)^{\frac{1}{2}}}\sin\left[\frac{1}{2}(-K)^{\frac{1}{2}}\cdot\frac{D}{C}\right]=z\frac{4\tan\frac{\gamma}{2}}{e^{\sigma\gamma}+Ke^{-\sigma\gamma}}. \tag{14.2}$$

If z is kept unchanged, but the position x of the two points is altered, D/C becomes a well-defined function

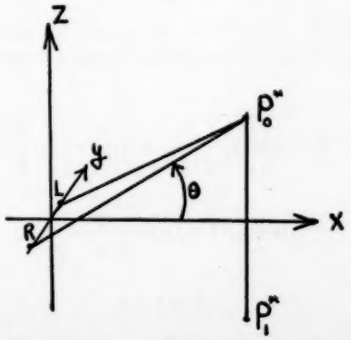

FIG. 28. Showing a line segment in the median plane.

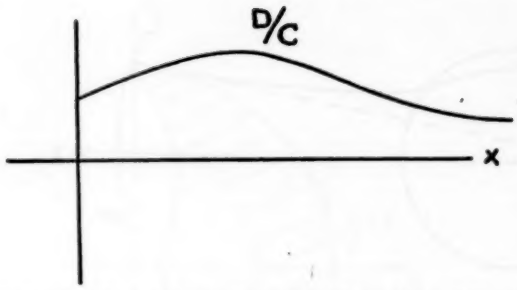

FIG. 29. Showing relative apparent size of line segment of Fig. 28 as a function of its position along the x axis.

of γ, that is, of the distance x of the two points from the observer. For small values of z we may write approximately

$$\frac{D}{C}=z\frac{4\tan\frac{\gamma}{2}}{e^{\sigma\gamma}+Ke^{-\sigma\gamma}}. \tag{14.3}$$

Thus D approaches zero if $x\to\infty$, unless $K=-1$, in which case a finite limit is reached asymptotically (Fig. 29). We conclude that constancy of size is maintained longer, the nearer to -1 the value of the observer's constant K is found to be.*

15. APPLICATIONS TO BINOCULAR OPTICAL INSTRUMENTS

The interpretation of the visual space as a metric space provides a theoretical basis for an investigation of binocular optical instruments, such as range finders, binocular field glasses, binocular microscopes, stereoscopic projectors, or even ordinary spectacles. Such instruments do not change the geometric character of the visual space but merely its coordination to the physical space. This fact may be expressed by stating that any optical instrument represents a certain point transformation of the visual space. Except for trivial cases, these transformations are not isometric, and therefore a metrically distorted view of external objects is introduced. A surface which originally gave the impression of a physically plane surface, may become apparently convex or concave. In a theoretical investigation of this situation the theory of curved surface embedded into a hyperbolic space thus finds a significant application.

16. INCORPORATION OF MOTION IN THEORY

The artificial restriction of the freedom of observation which has been introduced at the beginning is not maintained in usual visual sensations. We move our head, even our body, quite freely. This leads us to the problem of incorporating such motions into the theory of visual perception. Obviously, this problem is intimately related to the general problem of visual sensations of moving objects or of a moving observer. In order to approach this subject, a psychometric function should be established which measures the sensation of velocity of visual objects. Certain simple observations lead to the conclusion that this function is most probably given by a function of the type

$$w(v)=C\log\frac{c+v}{c-v}, \tag{16.1}$$

where c is a certain constant representing the extreme velocity of eye motions, whereas v is the image of the physical velocity in the ξ, η, ζ-space. This psychometric function is real valued only if $v<c$, which means that physical velocities $v>c$ are no longer recognized as velocity sensations. This corresponds to the fact that a moving light point produces the sensation of a streak of light if a certain velocity is exceeded. A space-time metric introduced to describe this situation mathematically will then be closely related to the space-time metric of special relativity.

* The same results are obtained qualitatively without the assumption $f(\gamma)=2e^{-\sigma\gamma}$. Instead of (14.3) we have

$$\frac{D}{C}=z\frac{2f(\gamma)}{1+\frac{K}{4}f^2(\gamma)}.$$

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Calculation of Index of Refraction of Gases from Absorption Data*

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A method for computing index of refraction of gases from absorption data is described. The index of refraction for CO_2 over a wide range of frequencies was calculated and found consistent with experimental data. The index of refraction of water vapor was calculated for the frequency range 0 to 7400 cm^{-1}.

I. INTRODUCTION

THE increasing interest in instrumentation in the infra-red region emphasizes the need for optical data for this part of the spectrum. Although there are considerable data on absorption by gases in the infrared region, the data on index of refraction are meager. It is therefore useful to have a convenient method of calculating index of refraction from absorption data. This paper describes one such method.

The expression for the absorption coefficient, κ, due to a single line is related to the intensity, S, and half-width at half-height, α, of the line and the frequency ν_0 of the line. The fractional absorption A measured experimentally however is an average over a frequency interval $\nu_0-\frac{1}{2}\Delta\nu$ to $\nu_0+\frac{1}{2}\Delta\nu$. Therefore one must compute an average value of κ over an interval $\Delta\nu$. This allows a computation of the function $S(\nu_0)$ from absorption data, if the interval between absorption lines is large compared to the line width. One can compute the contribution of a single line to the index of refraction, n, at any frequency ν in terms of the intensity $S(\nu_0)$ and the line width. The contribution from a band is obtained by adding the contributions from the lines in the band.

II. CALCULATION OF ABSORPTION

The average absorption over a frequency interval $\Delta\nu$ including a single line at ν_0 is

$$\frac{I_0-I}{I_0}=A=\frac{1}{\Delta\nu}\int_{\nu_0-\frac{1}{2}\Delta\nu}^{\nu_0+\frac{1}{2}\Delta\nu}(1-e^{-\kappa u})d\nu, \tag{1}$$

where I_0 and I are the initial and transmitted intensities, respectively, and u is the length of path traversed. The quantum-mechanical radiation theory gives the following expression for the absorption coefficient κ.[1]

$$\kappa=\frac{8\pi^3\nu N}{3hc}\frac{\sum_i\sum_j|\mu_{ij}|^2 f(\nu_{ij},\nu)e^{-W_j/kT}}{\sum_j e^{-W_j/kT}}, \tag{2}$$

where $\nu_{ij}=(W_i-W_j)/hc$ is the characteristic wave number associated with a transition between the states i and j, μ_{ij} is the matrix element of the electric moment and N is the number of molecules per cm^3. μ_{ij} determines the intensity of the line and $f(\nu_{ij},\nu)$ is the "shape factor"

$$f(\nu_{ij},\nu)=-f(\nu_{ij},\nu)$$
$$=\frac{1}{\pi}\frac{\nu}{\nu_{ij}}\left[\frac{\alpha}{(\nu_{ij}-\nu)^2+\alpha^2}+\frac{\alpha}{(\nu_{ij}+\nu)^2+\alpha^2}\right]. \tag{3}$$

For a single line $\begin{pmatrix}\mu_{ij}=\mu_0\\ \nu_{ij}=\nu_0\end{pmatrix}$ K can be written in the form

$$\kappa=8S\left(\frac{\nu}{\nu_0}\right)\frac{\alpha(\nu^2+\nu_0^2)}{(\nu^2-\nu_0^2)^2+4\alpha^2\nu^2}, \tag{4}$$

where

$$S=\frac{2\pi^2N}{3hc}\nu_0|\mu_0|^2\frac{e^{-W_j/kT}}{\sum e^{-W_j/kT}}(\mathrm{cm}^{-2})$$

determines the intensity of the line. μ_0 and S are both functions of ν_0. This expression is valid for

$$\alpha/\nu \text{ or } \alpha/\nu_0\ll 1.$$

The assumption is made that the line breadth is due to molecular collisions with a mean time interval

$$\tau=1/2\pi\alpha c.$$

If the lines are sharp (i.e., if $\alpha/d\ll 1$, where d is the distance between lines) and if $\Delta\nu\ll\nu_0$ the integration of (1) gives

$$A\Delta\nu=\frac{4\pi Su}{n}\left[1-\frac{1}{2!}\frac{1}{1!}(\tfrac{1}{2})X+\frac{1}{3!}\frac{1}{2!}(\tfrac{1}{2})(\tfrac{1}{2}+1)X^2\right.$$
$$\left.-\frac{1}{4!}\frac{1}{3!}(\tfrac{1}{2})(\tfrac{1}{2}+1)(\tfrac{1}{2}+2)X^3+\cdots\right], \tag{6}$$

where

$$X=4Su/n\alpha. \tag{7}$$

For very small path lengths A is proportional to the

* Work started while authors were employed at North American Aviation, Inc., Inglewood, California.

[1] J. H. Van Vleck and V. F. Weisskopf, Rev. Mod. Phys. **17**, 227 (1945).

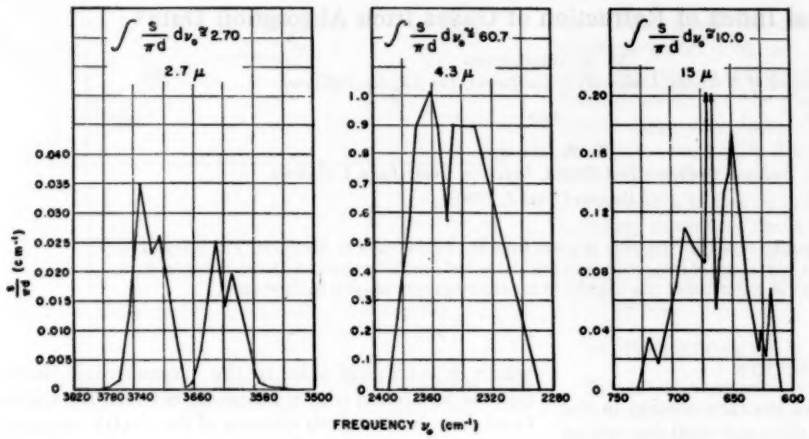

FIG. 1. Values of the absorption intensity, s/d, for CO_2 at S.T.P.

path length. For large path lengths ($X>\sim 3$ or 4) the asymptotic expansion of (6) gives[2]

$$A\Delta\nu=4(\pi/n)^{\frac{1}{2}}(Su\alpha)^{\frac{1}{2}}. \tag{8}$$

Equation (8) gives the usual square-root dependence on path length for relatively long path lengths. For a band with an average spacing between lines of d we take $\Delta\nu=d$ to obtain the average absorption from a line in the band to be

$$A=4\pi(u/n)^{\frac{1}{2}}(S/\pi d)^{\frac{1}{2}}(\alpha/d)^{\frac{1}{2}}. \tag{8a}$$

If A is known as a function of frequency ν_0 and path length u and (α/d) is known from band spectroscopic data, $S/\pi d$ can be calculated as a function ν_0. To reduce the data for A to standard density and temperature conditions we assume

$$S/S_S=\rho/\rho_S, \quad \alpha/\alpha_S=(\rho/\rho_S)(T/T_S)^{\frac{1}{2}}, \tag{9}$$

where ρ_S and T_S are the reference density and temperature, respectively.[3]

III. CALCULATION OF INDEX OF REFRACTION

The index of refraction is given by[1]

$$(n^2-1)=\frac{8\pi N}{3hc}\frac{\sum_i\sum_j|\mu_{ij}|^2[\nu_{ij}/(\nu_{ij}^2-\nu^2)]g(\nu_{ij},\nu)e^{-W_j/kT}}{\sum_j e^{-W_j/kT}}, \tag{10}$$

where

$$g(\nu_{ij},\nu)=\frac{(\nu^2-\nu_{ij}^2)^2+\alpha^2(2\nu_{ij}^2-\nu^2-\nu^4/\nu_{ij}^2)+\alpha^4(1-\nu^2/\nu_{ij}^2)}{(\nu^2-\nu_{ij}^2)^2+2\alpha^2(\nu^2+\nu_{ij}^2)+\alpha^4}. \tag{11}$$

For α/ν or $\alpha/\nu_0\ll 1$, the contribution to the index of refraction from a single line of frequency ν_0 is

$$n-1=\frac{2S(\nu_0)}{\pi}\frac{\nu_0^2-\nu^2}{(\nu_0^2-\nu^2)^2+(2\alpha\nu)^2} \tag{12}$$

which is the well-known classical expression.[4] If there are a large number of lines the index of refraction at any frequency ν is

$$n-1=\frac{2}{\nu^2}\int_{\text{all bands}}\frac{[S(\nu_0)/\pi d][(\nu_0/\nu)^2-1]}{[(\nu_0/\nu)^2-1]^2+(2\alpha/\nu)^2}d\nu_0. \tag{13}$$

For the range of integration far from ν Eq. (13) becomes

$$n-1=\frac{2}{\nu^2}\int\frac{S(\nu_0)}{\pi d}\frac{d\nu_0}{(\nu_0/\nu)^2-1}. \tag{13a}$$

[2] E. T. Whittaker and G. N. Watson, *Modern Analysis* (The Macmillan Company, New York, 1945), pp. 337, 342, 346.
[3] D. M. Dennison, Phys. Rev. **31**, 503 (1928).
[4] M. Born, *Lehrbuch der Optik* (Verlag. Julius Springer, Berlin, 1933).

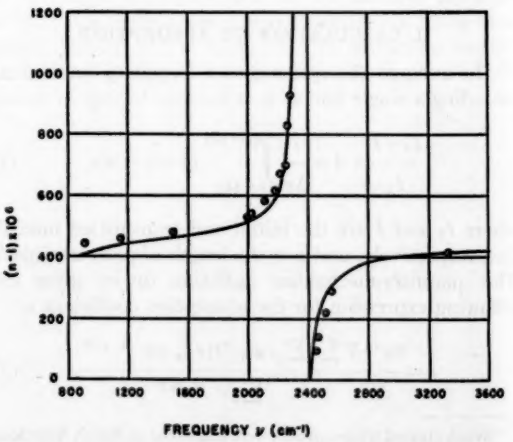

FIG. 2. Index of refraction for CO_2. Solid curve is computed. Points are experimental.

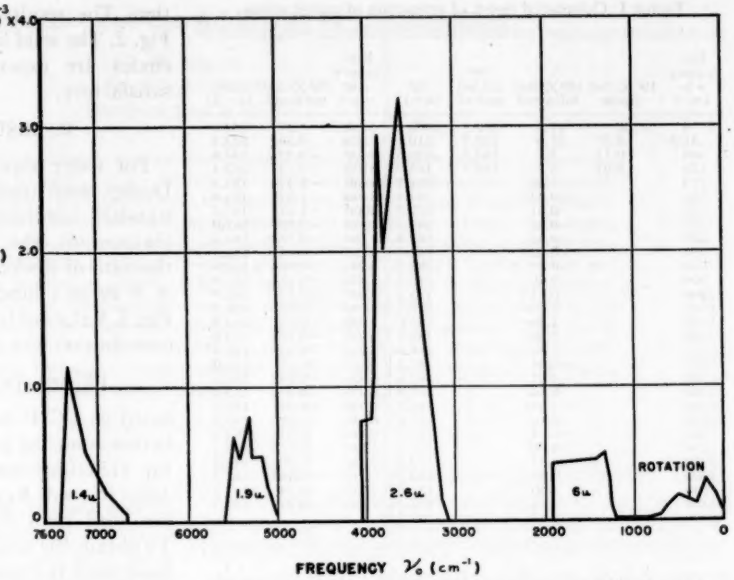

FIG. 3. Values of the absorption intensity, $S/\pi d$, for water vapor at 100°C and 1 atmos.

For the contribution from a band far from ν one can write

$$n-1=\frac{2}{\nu^2[(\bar{\nu}_0/\nu)^2-1]}\int_{\text{band}}\frac{S(\nu_0)}{\pi d}d\nu_0 \qquad (13b)$$

where $\bar{\nu}_0$ is the frequency of the center of gravity of the band. In many cases the contribution to the index of refraction from a band can be approximated by assuming S to be a constant over the band in which case

$$n-1=\frac{S}{\pi d\nu}\ln\left\{\left(\frac{\bar{\nu}_0+\nu-md}{\bar{\nu}_0+\nu+md}\right)\left[\frac{(\bar{\nu}_0-\nu+md)^2+\alpha^2}{(\bar{\nu}_0-\nu-md)^2+\alpha^2}\right]^{\frac{1}{2}}\right\} \qquad (14)$$

where $2md$ is the width of the band.

The index of refraction in the infra-red can be calculated by writing

$(n-1)$ = integral in Eq. (13) over all infra-red bands + a contribution Δn, from the optical range.

A value, $\Delta n'$, is first obtained at the lowest optical frequency ν' for which the index of refraction is known by taking the differences between the known n at that frequency and the calculated contribution from the infra-red bands. The value of Δn at any other frequency ν is then approximately $\Delta n=\Delta n'(\nu_1^2-\nu'^2)/(\nu_1^2-\nu^2)$ where ν_1 is the empirical frequency governing the optical dispersion.

For polar gases, such as water, the index of refraction at very low frequencies is markedly influenced by the permanent dipole moment, μ_0. At higher frequencies the effect of the permanent moment disappears because the dipole is unable to follow the rapidly alternating electric field. At intermediate frequencies the effects of both permanent and induced moments must be considered.

For a complex molecule such as water, the theoretical evaluation of (10) would be extremely difficult. In the absence of an experimental knowledge of S we cannot extrapolate the index of refraction from its values at higher frequencies. For ν very near zero the contribution to the index of refraction is mostly due to the permanent dipole and it can be shown in this case that expression (10) reduces to the well-known expression[1]

$$n^2-1=\epsilon-1=\frac{4\pi N}{3kT}\frac{\alpha^2}{\nu^2+\alpha^2}\mu_D^2. \qquad (15)$$

IV. RESULTS FOR CO_2

Experimental data for the index of refraction are available for a wide range of wave-lengths[5] including detailed data in the 4.3μ band.[6] The absorption data were taken from Martin and Barker,[7] Schaefer and Phillips,[8] and Tingwaldt.[9] The values of $S/\pi d$ computed from this absorption data in accordance with Eq. (8a) are given graphically in Fig. 1. The value of d from the experimental data (or calculated) is 1.56 cm^{-1} and the value of α was calculated theoretically from[3]

$$\alpha=(Na^2/c)(7.6kT/2\pi m)^{\frac{1}{2}},$$

where N is the number of particles per cm^3, m is the mass of the molecule and a is the molecular diameter. The calculated value of α at S.T.P. is 0.048 cm^{-1}, giving a value

$$d/\alpha=32.6.$$

This value is the same for all bands considered.

[5] O. Fuchs, Zeits. f. Physik **46**, 519 (1928).
[6] I.C.T. taken from Wetterblad, Diss., Upsala (1924).
[7] P. E. Martin and E. F. Barker, Phys. Rev. **41**, 291 (1932).
[8] Schaefer and Phillips, Zeits. f. Physik **36**, 641 (1926).
[9] Tingwaldt, Physik. Zeits. **35**, 715 (1934).

TABLE I. Calculated index of refraction of water vapor.

Frequency ν in cm^{-1}	$10^6\times(\Delta n)$ dipole	$10^6\times(\Delta n)$ infra-red	$10^6\times(\Delta n)$ optical	10^6 $(n-1)$	Frequency ν in cm^{-1}	$10^6\times(\Delta n)$ infra-red	10^6 $(n-1)$
0	2760	17.3	182.7	2960	3400	1.17	184.1
31.8	0.37	27.0	182.7	210.1	3500	0.54	183.4
50	0.11	5.7	182.7	188.5	3600	−0.22	182.6
150	0.01	3.2	182.7	185.9	3700	−0.73	182.1
250		−1.65		181.1	3800	−1.45	181.4
350		−0.33		182.4	3900	−1.12	181.8
450		−0.31		182.3	4000	−1.17	181.7
550		−0.52		182.2	4030	−0.89	182.0
650		−0.42		182.3	4250	−0.58	182.4
750		−0.022		182.7	4750	−0.25	182.7
850		0.22		182.3	5000	−0.075	182.9
900		0.40		183.1	5100	−0.14	182.9
1000		0.54		183.3	5200	−0.18	182.9
1100		0.763		183.4	5300	−0.33	182.8
1200		1.30		184.0	5400	−0.22	182.9
1300		2.06		184.7	5500	−0.59	182.6
1400		2.84		185.6	5600	−0.35	182.8
1450		−0.54		182.2	6000	−0.18	183.0
1500		0.11		182.8	6500	−0.095	183.1
1600		0.16		182.9	6600	−0.052	183.2
1700		−0.015		182.7	6700	−0.017	183.3
1800		−0.16		182.6	6800	−0.016	183.3
1900		−0.28		182.4	6900	0.013	183.4
2250		0.20		182.9	7000	0.015	183.4
2750		0.55		183.4	7100	0.0023	183.4
3000		0.88		183.7	7200	−0.063	183.3
3100		1.20		184.0	7300	−0.28	183.1
3200		1.41		184.2	7400	−0.37	183.1
3300		1.45		184.3			

The contribution from the optical region was determined by assuming it to be of the form

$$(n-1)_{\text{optical}} = A/(B-\nu^2).$$

A and B were determined by fitting experimental values of $(n-1)$ at $\nu=5000$ and 10,000 cm^{-1}. The variation of $(n-1)$ optical over the range of wavelengths considered in this calculation is very small compared to the variation in the total index of refraction. The results of the calculation are presented in Fig. 2. The solid lines are the computed curves, and the circles are experimental points. The agreement is satisfactory.

V. RESULTS FOR WATER VAPOR

For water vapor the absorption data tabulated by Dorsey were used.[10] The data were all reduced to a standard condition of 100°C and 1 atmos. using Eqs. (5a) and (6). The value of $\alpha_S=0.368$ cm^{-1} was based on the data of Becker and Autler.[11] The calculated values of $S/\pi d$ as a function of frequency ν_0 are presented in Fig. 3. Values of $(n-1)$ are given in Table I. The optical contribution was computed from the formula

$$10^6(\Delta n)\ \text{opt}=185.9\times 127.75/(130.0-1/\lambda^2)$$

based on I.C.T. data for the optical range. The contribution from the permanent dipole was computed from Eq. (15). The contributions from the infra-red bands down to $\nu=31.8$ cm^{-1} were computed by using the data for $S/\pi d$ from Fig. 3 in conjunction with Eq. (13). To obtain the contribution of that part of the rotation band from 31.8 cm^{-1} to 0 an empirical form of $S/\pi d$ was assumed in this region. The form was chosen so that the contribution at $\nu=0$ was consistent with the dielectric constant data. It appears that $S/\pi d=(S/\pi d)_{31.8}\times(\nu_0/31.8)^3$ is a reasonable empirical form in this region.

[10] N. E. Dorsey, *Properties of Ordinary Water Substance* (Reinhold Publishing Corporation, New York, 1940), Table 55, pp. 128–130.

[11] G. E. Becker and S. H. Autler, Phys. Rev. **70**, 300 (1946).

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Some Consequences of the Additivity of Luminosities

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Accepting the additivity of luminosities in spectral color-mixture throughout a wide range of luminosities as an experimentally established principle, certain definite conclusions can be drawn concerning the constitution of the visual sensory mechanism. It is shown that a trisensational sensory system could satisfy the additivity of luminosities exactly only in the event of a direct-proportionality relationship between visual sensation intensity and stimulus intensity, unless the luminosity coefficients of two of the three sensations were sensibly null. However, in a trisensational system in which sensation intensity obeys Fechner's law and more than one of the sensation luminosity coefficients has an appreciable value, the luminosity additivity law might hold to within the limit of observational error, but only if the spectral excitation curves of the elementary color-sensations overlap much more extensively than has usually been assumed. The form of surfaces of constant luminosity in a color-space representing a sensory system of the latter type is investigated. A sensory system in which luminosity is associated exclusively with a single element of the system would satisfy the additivity of luminosities unconditionally.

I. DEFINITIONS AND TERMINOLOGY

VISUAL sensation is characterized by two general attributes which in everyday language are called color and brightness. As the words are used here, color relates to sensation quality, while brightness relates to sensation intensity. But each of these words has several distinct though similar meanings in ordinary usage. In the terminology of colorimetrics, the meaning indicated above for color has been taken over by the specific term *chromaticity*, and the substantive *color* is reserved to denote a unique kind of visual impression defined as to both chromaticity and brightness (in the above sense). However, the fact this special definition has been assigned to the word color need not preclude its occasional use in one of its non-technical senses in a discussion devoted to colorimetrics. In such instances the context should indicate the meaning intended.

In dealing with the brightness phase of visual sensation it is necessary to differentiate between two distinct entities. These are (1) a sensation attribute, and (2) a numerical quantity specifying the latter but associated primarily with stimulus characteristics. The second of these entities is now called *luminosity*. Formerly the two terms brightness and luminosity were used interchangeably, and usually no clear-cut distinction was drawn between concepts (1) and (2). Some word is needed to designate the sensation attribute corresponding to luminosity, and since the common meaning of the root *bright* refers to appearance and hence to a property of sensation, and also because of its historical use in this connection, *brightness* seems to be the most suitable term for the purpose, despite the fact that it has an assigned definition with respect to light intensity in photometry as well as several somewhat related meanings in common parlance.

When uniform light of constant intensity incident upon the retina of the eye gives rise to visual sensation, the brightness of the cerebral image thus evoked is a function of the intensity of the exciting light or stimulus, and also of its spectral energy distribution. If two neighboring retinal areas are illuminated by stimuli of the same spectral distribution, it is easy under suitable conditions to judge whether both areas appear equally bright, or, if not, which is the brighter. This faculty of brightness-judgment is utilized in "homochromatic" photometry to equalize and by that means to measure objective light intensities. If the two illuminated areas are not "the same color," that is, if the visual impressions set up by them differ in chromaticity, it is still possible to form a judgment as to equality of brightness between them, although the difficulty of doing so may be greatly increased. But if the two colors closely resemble one another, as is true, for example, in the case of two colors lying near each other in the spectrum, such "heterochromatic" brightness comparisons can be made with nearly the same high degree of precision as that obtainable in homochromatic photometry. The results of such comparisons are however dependent to some extent upon a personal factor, since the wave-length-response characteristics of the individual eye are involved. Employing a step-by-step procedure, uniform illuminants composed respectively of adjacent narrow bands of spectral wave-lengths have been regulated in intensity so as to evoke a series of equally bright colors, as adjudged by certain observers whose group averages are presumed to represent normal color-vision. The reciprocals of the intensities (energy dissipations per unit retinal area) of these stimuli are called the relative intrinsic luminosities of the spectral colors, and the curve obtained by plotting them against wave-length is called the luminosity curve of the equal-energy spectrum.

This curve, to which frequent reference must be made at one stage of the present discussion, continues to pose a troublesome terminological problem. The historical "visibility curve" designation, long regarded as something less than satisfactory, is currently in disfavor, but on the other hand neither the unwieldy full description of the curve given above nor the rather vague ex-

pression "the luminosity curve" to which the latter is sometimes shortened in current writing adequately takes its place under all circumstances. Choosing what seems in the present connection to be the lesser of two evils, or perhaps more accurately the least of three, the outmoded designation will subsequently be employed.

II. THE LUMINOSITY ADDITIVITY LAW

If two differently colored stimuli are superposed on the retina by the process known as spectral color-mixture, the resultant color seen by the observer in general differs from either of the component colors not only in chromaticity but also in brightness. The laws governing the changes in chromaticity which occur under these circumstances were established by the color-matching experiments of Clerk Maxwell and others. Only in comparatively recent times, however, has the rule by which luminosities combine become known with equal definiteness. Although this result was foreshadowed by certain earlier observations, it remained for Ives[1] to demonstrate that the luminosity of the resultant color in spectral color-mixture is equal to the sum of the luminosities of the component colors, as nearly as can be determined by precise measurements. This principle, now known as the "law of the additivity of luminosities" or simply "the additivity of luminosities," has been subjected to many tests and has been found valid except at very high and very low brightness levels. In considering theories of visual sensation from an analytical standpoint, the tendency has been to emphasize the chromaticity aspect of visual sensation and to neglect the equally fundamental brightness aspect. Clearly, the additivity of luminosities constitutes an additional condition over and above the laws of spectral color-mixture relating to chromaticity, which any proposed visual sensory mechanism must satisfy in order to be acceptable.

III. BRIGHTNESS IN A TRISENSATIONAL SYSTEM

Two opposed views have been advanced concerning the feature of the visual sensory mechanism through which brightness comes into being. Upon one view, brightness at photopic levels is normally a summation, or cerebral integration, so to speak, of separate intensity effects contributed by several "elementary color sensations." This concept of brightness was a natural outgrowth of the trisensational (Young-Helmholtz) theory of vision and has generally been regarded as a corollary of that theory. Upon the other view, brightness is exclusively or almost wholly the adjunct of a single factor of the sensory system. The Hering "opponent-colors" theory has usually been looked upon as the prototype of theories of vision embracing the latter concept, although a variety of such have been proposed. The trisensational concept of brightness is the older of the two, and is probably the more widely held today.

[1] H. E. Ives, Phil. Mag. 24, 845 (1912).

1. Luminosity Coefficients

If all colors are synthesized from three fundamental color sensations, as envisioned by the trisensational theory, any color C can be specified in terms of amounts or intensities of its sensation components by a Maxwell color-equation of the form

$$C \equiv \sum x_i X_i \quad (i=1, 2, 3) \tag{1}$$

where X_1, X_2, X_3 represent arbitrary unit excitations of the respective fundamental sensations, and x_1, x_2, x_3 are numerical coefficients sometimes called the "responses" of the fundamental sensations. Since C is specified by (1) as to both chromaticity and brightness, there is associated with it a certain luminosity l. Suppose three colors are chosen, out of which a number of other colors can be produced by combining them in various proportions by the process of spectral color-mixture (but no one of which can be matched by a mixture of the other two). Let us say these colors are a red $R \equiv \sum x_{iR} X_i$, a green $G \equiv \sum x_{iG} X_i$, and a blue $B \equiv \sum x_{iB} X_i$, having luminosities, respectively, l_R, l_G, l_B. By the law of the additivity of luminosities, any color $Q = rB + gG + bB$ produced by combining them in the proportions indicated by the numerical coefficients r, g, b must have luminosity $l_Q = rl_R + gl_G + bl_B$. This can only hold true if the fundamental sensations themselves have intrinsic luminosities given by the three equations

$$\left.\begin{aligned} l_1 &= |l_R x_{2G} x_{3B}| / |x_{1R} x_{2G} x_{3B}| \\ l_2 &= |x_{1R} l_G x_{3B}| / |x_{1R} x_{2G} x_{3B}| \\ l_3 &= |x_{1R} x_{2G} l_B| / |x_{1R} x_{2G} x_{3B}| \end{aligned}\right\} \tag{2}$$

where the numerators and denominators of the fractions are determinants specified in the usual way by the terms of their principal diagonals. The l_i are called the *luminosity coefficients* of the respective fundamental sensations. Their values obviously depend on the arbitrarily chosen unit excitations of the sensations and also on the unit selected for the measurement of luminosity, but once these magnitudes have been fixed, the l_i are automatically fixed by (2). All colors being produced, as it were, by the admixture of the fundamental sensations, the luminosity l of any color $C(x_i)$ must be the sum of the luminosities of its sensation components, so that in general

$$l = \sum x_i l_i. \tag{3}$$

2. Sensation Excitation Curves

If the sensation responses corresponding to the colors of a spectral sequence are plotted separately against wave-length, they determine three "sensation excitation curves." By (3), at every point on the wave-length scale the products of the ordinates of the excitation curves and the respective sensation luminosity coefficients must add up to the ordinate of the luminosity curve (luminosity plotted against wave-length) of the

given spectral sequence. König[2] made use of this deduction from the trisensational theory in an attempt to derive spectral excitation curves for the fundamental sensations of color. From certain considerations which need not concern us here, König determined what he believed to be the abscissae (on the wave-length scale) of the points of intersection of the sensation excitation curves. This information was not sufficient, however, to establish the curves. For the needed additional information König relied upon a premise now considered questionable, namely, the existence of distinct kinds of color-blindness characterized respectively by the lack of different elementaries. Nevertheless, König's sensation curves have been rather generally "accepted" in the sense of being looked upon as typifying the elementary color-sensations envisioned by the Young-Helmholtz theory.[3] König's sensation excitation curves, slightly modified,[4] are shown in the upper graph in Fig. 1.

Most subsequent attempts to establish three elementary color-sensations have resulted in excitation curves more or less similar to those of König. This has not been universally true, however. A noteworthy exception is to be found in the excitation curves proposed by Hecht.[5] Hecht pointed out that although König's sensation curves incorporate color-mixture and spectral luminosity data, their coordination is not apparent with certain other quantitative experimental data, such as those pertaining to visual acuity, chromaticity-difference sensibility, and the "subjective saturation" of spectrum colors as variously defined. In an effort to obtain representation of data of these types as well as those upon which König's sensation curves are based, Hecht evolved a set of curves which overlap to the extent of being nearly coincident and closely resemble those shown in the lower portion of Fig. 1, to be explained later.

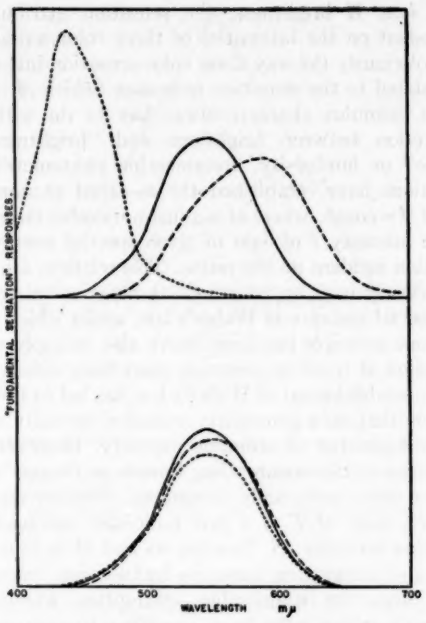

FIG. 1. Above—König's sensation-excitation curves, slightly modified. (See reference 4.) Below—fictitious sensation-excitation curves derived from König's to show the extent of overlapping of the curves required for the additivity of luminosities to hold within one percent in a trisensational system obeying Fechner's law.

3. The Visibility Curve

The bearing of the brightness aspect of visual sensation upon the nature of its underlying mechanism was investigated by Troland.[6] As more and more experimental data pertaining to brightness characteristics in trichromatic vision have accumulated, it has become increasingly apparent that the visibility curve of the normal eye has a very definite form. Upon the basis of the then available data, Troland showed that when allowance was made for the selective transmissivity of the macula lutea or "yellow spot" on the retina through which light reaching the centrally located retinal receptor-organs must pass, the visibility curve assumed an almost perfect symmetry, being in fact the locus of the probability function $h=\exp[-0.0002705(\lambda-555)^2]$ very nearly. Troland deemed it unlikely the substantially perfect symmetry of the visibility curve would break down into the irregular shapes of König's sensation excitation curves, and drew the alternative conclusions that either the sensation excitation curves of the trisensational theory overlap much more extensively than those determined by König and are themselves approximately of the probability form, or else "luminosity [brightness] is due to a single . . . process in the retina, and is not to be attributed to a summation of the response intensities of three or more color processes." Troland adduced other considerations in support of this view, among them the fact that the visibility curves for the color-deficient outer zones of the normal retina are almost identical in form to the selectivity-compensated foveal curve; the inference being that the form of the visiblity curve is independent of the lack or deficiency of one or more of the elementary color processes, which consequently cannot be supposed to contribute to over-all brightness in such a way as to affect its shape.

4. Fechner's Law

A further objection can be brought against the traditional trisensational concept of brightness, for it can be shown that *in classical form the trisensational theory of vision is at variance with the luminosity addi-*

[2] A. König and C. Dieterici, Zeits. f. Psychol. u. Physiol. d. Sinnesorgane **4**, 241 (1892).
[3] D. B. Judd, Trans. Illum. Eng. Soc. **36**, 351 (1941).
[4] L. T. Troland, J. Opt. Soc. Am. **6**, 548 (1922).
[5] S. Hecht, J. Opt. Soc. Am. **20**, 231 (1930); **21**, 615 (1931).
[6] L. T. Troland, Trans. Illum. Eng. Soc. **11**, 947 (1916); J. Opt. Soc. Am. **6**, 3 (1922).

tivity law. If brightness, the sensation attribute, is dependent on the intensities of three color sensations, then obviously the way these color-sensation intensities are related to the sensation responses (which of course reflect stimulus characteristics) has to do with the connection between brightness and "brightness response" or luminosity. Innumerable photometric observations have established the so-called photometric law $\delta I/I = \text{const.}$, where δI is a just noticeable increment of the intensity I of light of given spectral energy distribution incident on the retina. This relation, found to hold closely over an intermediate range of intensities, is a special instance of Weber's law, under which name the same principle has been shown also to apply to the excitation of types of sensation other than visual.

The establishment of Weber's law has led to the supposition that, as a generality, sensation intensity varies as the logarithm of stimulus intensity. However, the soundness of this assumption, known as *Fechner's law*, has not been universally recognized. Fechner equated Weber's ratio $\delta I/I$ to a just noticeable increment of sensation intensity δS. Treating δS and δI as infinitesimals and integrating gave $S = \log I + \text{const.}$ Involving as it does the unprovable assumption $\delta S = \text{const.}$, Fechner's critics have been unwilling to concede his hypothesis the status of a "law" or established principle. While their contention is probably justified, nevertheless it can hardly be denied that "Fechner's law" is a plausible assumption. It provides a facile explanation of the experimental results summarized by Weber's law. If sensation intensity does not vary as the logarithm of stimulus intensity, then by what law are the two connected? So far no other relation has been suggested.

5. Condition for Exact Additivity

It seems quite certain, however, that sensation intensity and stimulus intensity do not vary by direct proportionality, and yet *that is the only relation between the two* which could bring about the *exact* additivity of luminosities, if substantial additive components of brightness are contributed by two or more independently varying sensations. Since the elementary sensations must act independently of one another in order to account for the chromatic aspects of spectral color-mixture, each must contribute a separate component of brightness (supposing its luminosity coefficient to be greater than zero), which must be some function $S_i(x_i)$ of its own response alone. These brightness components must combine on some sensory level above the peripheral to give rise to over-all brightness, and if this takes place by a simple additive process, as of course is implicit in the classical trisensational brightness concept, we should have for brightness, $B = \sum S_i(x_i)$. (Another way the components of brightness might combine will be mentioned farther on.) But when B is constant, l is constant, and conversely, and when $l = 0$, $B = 0$ (this is sensibly true by extrapolation from the photopic region downward) and since $l = \sum x_i l_i$, *it follows of necessity that B is a linear homogeneous function of the x_i*, in fact the function $k\sum x_i l_i$ where k is a constant, and hence that each function $S_i(x_i)$ has the form $kl_i x_i$. Since by definition brightness is identified with sensation intensity, the S_i are in fact the intensities of the elementary color-sensations, which consequently are proportional to the respective x_i.

6. Additivity and Fechner's Law

Although direct proportionality between sensation intensity and stimulus intensity is demanded under these conditions for luminosities to add with analytical exactitude, they could, however, add to within the limit of observational error even in the event of a logarithmic sensation-stimulus relation, provided the spectral excitation curves of the elementary color-sensations overlap to a sufficient degree. It is possible to estimate approximately the extent of overlapping necessary in a trisensational system obeying Fechner's law to bring about the apparent additivity of luminosities to within any given limit of observational error. Let the intensities of the elementary sensations be respectively $S_i = a_i \log x_i$, the a_i being the reciprocals of Weber's constants for the respective elementaries. Brightness is then $B = \sum a_i \log x_i$. Let us now devise a color-space that is homogeneous throughout (i.e. we do not differentiate between photopic and scotopic regions), in which the coordinates are the x_i. In this space all colors of like brightness lie on a surface whose equation is $\sum a_i \log x_i = \text{const.}$, which may also be written

$$x_1^{a_1} x_2^{a_2} x_3^{a_3} = \text{const.} \tag{4}$$

To designate such a surface of uniform brightness (and hence constant luminosity) we shall employ Schrödinger's term *isolychnic*,[7] since it is companionate to the established term *isochrome* signifying a line emanating from the origin of the color-space, the locus of colors alike in chromaticity but differing in brightness. Equation (4) is the equation of a family of surfaces each of which is an isolychnic. These curved surfaces are convex toward the origin of coordinates, and in fact do not intersect the coordinate planes, which are asymptotic to them. Each is tangent, at approximately the point on it nearest the origin, to some plane $\sum x_i = \text{const.}$ cutting the three coordinate axes at equal distances from the origin. Now, the planes of the family $\sum x_i = \text{const.}$ would have to be the isolychnics of a system (assuming the X_i to be chosen so that $l_1 = l_2 = l_3$) in which luminosities were exactly additive. But in our present system luminosities are to be additive within the limit of experimental error, hence all real colors of like brightness must be crowded into the area on one of these curved surfaces immediately surrounding its point of tangency with one of these planes. This of course is equivalent to saying that the elementary sensations must participate to a nearly equal relative degree in all real colors, or in

[7] E. Schrödinger, Ann. d. Physik **63**, 397–481 (1920).

other words that their spectral excitation curves must overlap extensively. The values of the a_i are unknown; however, we seek to establish the *minimum* required degree of concurrence of the elementaries to cause the system to agree with experiment within the limit of observational error, and it can be shown that the minimum will occur when $a_1=a_2=a_3$. If in reality the a_i are not all equal, a still greater degree of concurrence must occur than that which we shall determine. If $a_1=a_2=a_3$, Eq. (4) becomes

$$x_1x_2x_3=\text{const.} \tag{5}$$

The point of tangency of each of these latter surfaces with a plane of the family $\sum x_i=\text{const.}$ lies on the isochrome $x_1=x_2=x_3$.

In the system of which the surfaces (5) are the isolychnics, let us consider the particular plane $\sum x_i=3$. It is tangent at the point (1, 1, 1) to the surface $x_1x_2x_3=1$, and is intersected by all of the surfaces $x_1x_2x_3<1$. The traces of the latter form closed curves on the plane concentric about the point (1, 1, 1). Figure 2 represents the portion of the plane $\sum x_i=3$ contained in the positive octant, and shows some of these traces. Since all points on any given isolychnic are the same brightness, this set of concentric curves, a few of which are shown on the diagram, is in effect a system of brightness (and luminosity) contours on the plane. The choice of the unit excitations X_i of the elementary sensations being optional, they may be chosen so that $l=\frac{1}{3}\sum x_i$ along the isochrome $x_1=x_2=x_3$; and in that case at the center of the diagram $l=1$. The innermost curve is the trace of the surface tangent to the plane $\frac{1}{3}\sum x_i=0.99$ and is hence the locus of $l=0.99$, and in a similar way the other luminosity contours indicated on the diagram have been established. It is evident that brightness on the plane of the diagram is greatest at the point (1, 1, 1), whence it falls off at an increasing rate in every direction.

In consequence of this distribution of brightness, the mixture of two neighboring colors lying on the contour $l=0.99$ would have a one percent lower luminosity than that of the mixture of two colors lying on it on opposite sides of the center. Probably a difference even less than one percent could be detected experimentally (Ives obtained an agreement $|1-\int l(\lambda)d\lambda/[\textit{luminosity of undispersed illuminant}]|<0.005$), therefore, since no such difference has been observed, the contour $l=0.99$ sets an outside limit for the boundary of the area of real colors on the plane of the diagram, and *the space domain of real colors must in this system be confined to a cone of angular dimension no greater than the solid angle subtended at the origin of coordinates by the area bounded by this approximately circular contour.*

We have arrived at this result on the assumption that brightness is the simple sum of the intensities of the elementary color-sensations, but this is not the only possible assumption. Helmholtz[8] gave reasons for assuming a "root-sum-square" relation between brightness and the elementary sensation intensities. Schrödinger[7] has already shown (with a different objective in view) that this relation, *viz.* $(dB)^2=(dS_1)^2+(dS_2)^2+(dS_3)^2$, leads, in the case where $a_1=a_2=a_3$, to the same family of isolychnics $x_1x_2x_3=\text{const.}$ we obtain here. In the general case in which the a_i are unequal (not considered by Schrödinger) it can be demonstrated that the isolychnics following upon Helmholtz's assumption are the surfaces $x_1^{a_1^2}x_2^{a_2^2}x_3^{a_3^2}=\text{const.}$ These surfaces are of the same type, but do not belong to the same family for given values of the a_i, as those designated by (4), except in the particular case already noted where the a_i are equal. Here again, the surface with least mean curvature at its point of tangency with a given plane $\sum x_i=\text{const.}$ is that for which the a_i are equal, i.e. a surface $x_1x_2x_3=\text{const.}$; so that the minimum required degree of concurrence of the elementary sensations occurs under the same conditions and is the same as before. Therefore, whichever one we make of these two most likely assumptions in regard to the relation of brightness to the elementary sensation intensities, we arrive at the selfsame result, leading to the conclusion that in a system of the prescribed type, extreme differences of chromaticity must depend upon merely marginal relative variations among the elementary sensation intensities.

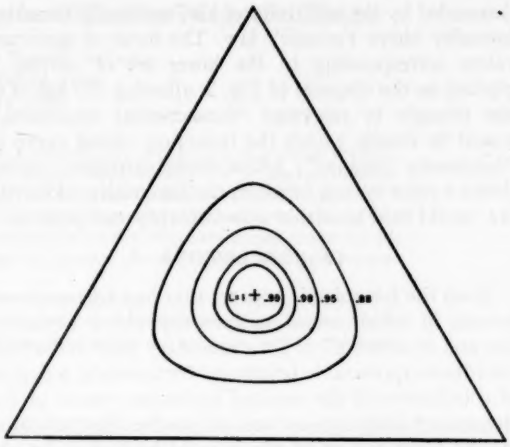

FIG. 2. Luminosity contours on a plane $\Sigma x_i=\text{const.}$ in a color-space representing a trisensational system obeying Fechner's law. Weber's ratio taken the same for all three elementary color-sensations.

Below the König sensation-excitation curves in Fig. 1 is shown another set derived from them, allowing the intermediate curve to remain unchanged and the intersections of the corresponding curves to occur at the same places on the wave-length scale. The lower set illustrates the degree of overlapping of the curves

[8] H. v. Helmholtz. *Physiol. Optik* (Voss. Leipzig, 1896), pp., second edition 444–458.

demanded by the additivity of luminosities, if sensation intensity obeys Fechner's law. The locus of spectrum colors corresponding to the lower set of curves, if plotted on the diagram of Fig. 2, allowing the apices of the triangle to represent "fundamental sensations," would lie wholly within the innermost closed curve or "luminosity contour"; hence these excitation curves define a color system in which the luminosity additivity law would hold to within approximately one percent.

IV. CONCLUSIONS

From the foregoing it appears that in a trisensational system in which sensation intensity obeys Fechner's law and in which all of the elementary color sensations contribute appreciable brightness components, a degree of coincidence of the spectral excitation curves of the elementary sensations at least as great as that indicated by the lower curves of Fig. 1 is to be looked for. As already noted, the sensation curves proposed by Hecht bear a close resemblance to these curves and do exhibit about this degree of coincidence. Assuming Fechner's law, Hecht's color system might be expected to fulfill the luminosity additivity requirement within the present limit of observational error. The same cannot be said, however, of König's and most other trisensational systems that have been advanced up to this time.

However, *if brightness were generated by only one factor of the visual sensory mechanism*, luminosities would then be strictly additive in spectral color-mixture irrespective of the law connecting sensation intensity and stimulus intensity. Various types of sensory system having this characteristic are conceivable. The simplest would be a system comprising three elementary color-sensations, one of which greatly exceeded the other two in intensity in all real colors. Brightness being in the nature of a manifestation of over-all intensity of visual sensation, in a system of this kind brightness must be contributed altogether or almost altogether by the predominating color sensation. Consequently the luminosity coefficients of the other two elementaries would be zero or sensibly so. In that event two of the right-hand terms in (3), say the first and third, would be negligible, and (3) would become simply $l = x_2 l_2$. The excitation curve of the intermediate elementary would then have the form of the visibility curve. The system would have characteristics superficially similar to those of the I.C.I. Standard Observer color system,[9] the primaries of which (not, of course, presumed to correspond to fundamental sensations) have been chosen so that the luminosity coefficients of two of them are zero. This version of the trisensational theory satisfies the additivity of luminosities unconditionally.

In the Hering opponent-colors theory, brightness is assumed to be principally associated with the white phase of the white-black process, the green-red and yellow-blue processes supposedly making secondary brightness contributions which may be either positive or negative in sign. Schrödinger[10] showed that the positive and negative phases of the Hering retinal processes can be represented analytically by allowing two of the three responses of a ternary system to have negative as well as positive values. Neglecting the brightness contributions of the two "chromatic" processes, Schrödinger assigned them zero luminosity coefficients, so that the third response, corresponding to the positive or white phase of the white-black process, became proportional to luminosity. Thus this system also satisfies the additivity of luminosities.

By associating brightness with chromatically neutral sensation quality (in the sense of the trisensational theory, although Hering looked upon white as a positive chromatic value) the Hering theory avoids the psychological difficulty inherent in assigning the capacity to generate brightness exclusively to only one of three color sensations on a seemingly comparable footing from the standpoint of their respective contributions to the chromaticity phase of vision. However, the provisions of the Hering theory by no means represent the only conceivable arrangement that would have this advantage, and various others have been proposed. Without regard to its possible significance in connection with any particular theory of color-vision, the existence within the visual sensory mechanism of a unitary agency that is chiefly responsible for the luminosity characteristic in photopic vision has been repeatedly suggested by experimentalists, and numerous facts have been cited which seem to point in that direction. The potential importance of this possibility is self-evident.

[9] D. B. Judd, J. Opt. Soc. Am. 23, 359 (1933).
[10] E. Schrödinger, Sitz. Preuss. Akad. Wiss. (Wien) IIa, 134, 471 (1925).

Changes in g-Values, in a Spectrum, for Different Magnetic Fields

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Based on the theory of the partial Paschen-Back effect a quantitative explanation is given of the fact, recently discovered by the authors, that an atomic energy level of Mn I, namely $z\,^6F°_{1\frac{1}{2}}$, has two different values for the Landé splitting-factor g: one for each pair of the magnetic levels $M=\pm 1\frac{1}{2}$ and $\pm 0\frac{1}{2}$.

Attention is called to the fact that g-values, in cases such as those observed in Mn I, experience important alterations when the magnetic field is increased from about 40,000 oersteds, which is the magnitude of fields used in the past, to about 80,000, as actually used in observing Zeeman patterns at M.I.T. for the purpose of analyzing spectra.

It is pointed out that if g-values accompany a list of term-designations and term-values, it is desirable to specify the magnitude of the magnetic field to verify the correctness of the designations given in the analysis of the spectrum. Otherwise any alterations which the g-values may undergo will not be correctly interpreted.

RECENTLY[1] the authors have given an interesting case of an atomic energy state of the manganese atom, that of the level $z\,^6F_{1\frac{1}{2}}$, whose two pairs of magnetic levels, $M=\pm 1\frac{1}{2}$ and $M=\pm 0\frac{1}{2}$, have different g-values: 1.067 and 1.003, respectively.

The observed variation of g-values was tentatively ascribed to displacements which the magnetic levels experience owing to the proximity of other levels with the same M belonging to $z\,^6F_{0\frac{1}{2}}$. The hypothesis was based on the observed fact that the change in g-value in $z\,^6F_{1\frac{1}{2}}^{\pm 0\frac{1}{2}}$ was equal, and of contrary sign, to that observed in $z\,^6F_{0\frac{1}{2}}^{\pm 0\frac{1}{2}}$.

We are now in a position to prove this hypothesis quantitatively and, at the same time, to give the reasons that have concurred in this particular case to make the change in g-value so evident.

In the theory of the partial Paschen-Back effect[2] the magnitude of the displacement of a magnetic level, due to the interaction with another level of the same M-value, and belonging to each of two consecutive levels of the same spectral term, is given by

$$\epsilon = I^2/\delta. \tag{1}$$

In this equation ϵ represents the displacement, δ is the distance between the two repelling levels, and I is the *interaction factor* as given by Eq. (2). The three magnitudes are given in Lorentz units.

$$I=\left[\frac{(J-L+S)(J+L-S)(L+S+1+J)(L+S+1-J)}{4J^2(2J-1)(2J+1)}\right]^{\frac{1}{2}}(J^2-M^2)^{\frac{1}{2}}. \tag{2}$$

Equation (2) shows that I is a function of M^2, which means that the I-values are not affected by the sign of M. The same displacements are expected, in magnitude and sign, in two sub-levels $-M$ and $+M$ of the same atomic levels. Owing to this fact, the magnetic components of the same order, on each side of the central line in a pattern, show the same displacements and in the same sense, thus keeping their distances unperturbed. In calculating g-values it is the usual practice to take advantage of these circumstances to eliminate distortions due to partial Paschen-Back effect.

This general procedure of determining g-values will give serious errors in such cases as that of Mn I considered here. For a better understanding of this we have selected an arbitrary example. Two atomic levels $T_{1\frac{1}{2}}$ and $T_{0\frac{1}{2}}$ (consecutive in the same term T) and their magnetic levels $M=\pm 0_{\frac{1}{2}}$ are given in Fig. 1. The distance between the two atomic levels is δ and those between the magnetic levels are $g_{1\frac{1}{2}}$ and $g_{0\frac{1}{2}}$. These separations represent the corresponding g-values. We have selected $g_{1\frac{1}{2}} > g_{0\frac{1}{2}}$. The distance between the two negative magnetic levels is indicated by δ^- and that between the positive by δ^+.

If we first suppose that δ is large compared with $g_{1\frac{1}{2}}$ and $g_{0\frac{1}{2}}$ (this is not the case of Fig. 1), the distances δ^- and δ^+ can be taken equal to δ. The same approximation can be made, though δ is not large, if $g_{1\frac{1}{2}}$ and $g_{0\frac{1}{2}}$ do not differ much.

In these very usual cases Eq. (1) will give equal displacements ϵ for levels $-M$ and $+M$ (of the same

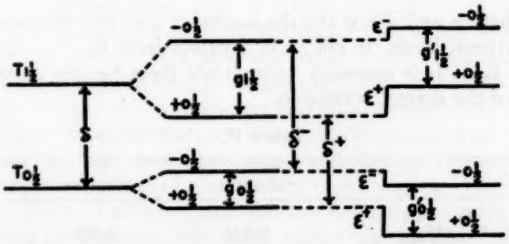

FIG. 1. Shift of magnetic levels due to Paschen-Back interaction.

[1] M. A. Catalán and R. Velasco, Proc. Roy. Soc. **A63**, 917 (1950).

[2] C. C. Kiess and G. Shortley, J. Research Nat. Bur. Stand. 42, 183 (1949).

TABLE I.

Atomic level	M	$M\cdot a\cdot g$	ϵ	$\epsilon+M\cdot a\cdot g$	ag'(cm^{-1})	g'(L.U.)
$z\,^6F_{1\frac{1}{2}}$	$-0\frac{1}{2}$	−2.11	−1.09	−3.20	3.92	0.990
	$0\frac{1}{2}$	2.11	−1.39	0.72		
$z\,^6F_{0\frac{1}{2}}$	$-0\frac{1}{2}$	1.32	1.09	2.41	−2.34	−0.591
	$0\frac{1}{2}$	−1.32	1.39	0.07		

atomic level). I being the same, and the distances also being the same for $-M$ as for $+M$, the resulting ϵ^- and ϵ^+ must be equal. In such cases the ordinary methods of determining g-values will give accurate results.

But in cases, such as that represented in Fig. 1, with a *large difference between the g-values* $g_{1\frac{1}{2}}$ *and* $g_{0\frac{1}{2}}$, the distances δ^- and δ^+ are no longer equal. Equation (1) when applied to pairs of levels with unequal distances, in spite of the equality of I-values, will give different ϵ-values: ϵ^- will be smaller than ϵ^+.

In Fig. 1 the perturbations ϵ^- and ϵ^+ are applied to the magnetic levels from $T_{1\frac{1}{2}}$ in an opposite direction to those from $T_{0\frac{1}{2}}$. The resulting perturbing levels are separated by new values $g'_{1\frac{1}{2}}$ and $g'_{0\frac{1}{2}}$.

If the new separations, the new g-values, are compared with the old ones, it will be seen that $g_{1\frac{1}{2}}$ has been decreased by the same amount as $g_{0\frac{1}{2}}$ is increased. The *g-values have both been altered*, but their sum remains unaltered.

We are now prepared to consider quantitatively the case of levels $z\,^6F_{1\frac{1}{2}}$ and $z\,^6F_{0\frac{1}{2}}$ of Mn I. Here we have two pairs of interacting levels: $z\,^6F_{1\frac{1}{2}}^{-0\frac{1}{2}}$, $z\,^6F_{0\frac{1}{2}}^{-0\frac{1}{2}}$ and $z\,^6F_{1\frac{1}{2}}^{+0\frac{1}{2}}$, $z\,^6F_{0\frac{1}{2}}^{+0\frac{1}{2}}$. The Landé g-values for levels $^6F_{1\frac{1}{2}}$ and $^6F_{0\frac{1}{2}}$ are 1.067 and −0.667, respectively. The difference between these values, 1.733, being very great, makes this case analogous to the arbitrary one explained above.

For simplicity in the comparison with the experimental results we shall use cm^{-1} in this case instead of Lorentz units. Equation (1) for the interaction measured in cm^{-1} can be written

$$e=I^2a^2/d, \tag{3}$$

where e and d are the displacement and the distance between levels, in cm^{-1}. As I-values from Eq. (2) are in L.U., it is necessary to multiply them by the value a of the *normal separation*.

TABLE II.

	Calculated	Observed
$z\,^6F_{1\frac{1}{2}}^{\pm0\frac{1}{2}}$	0.990	1.003
$z\,^6F_{0\frac{1}{2}}^{\pm0\frac{1}{2}}$	−0.591	−0.598
Sum	0.399	0.405

TABLE III.

Atomic level	M	$M\cdot a\cdot g$	ϵ	$\epsilon+M\cdot a\cdot g$	ag'(cm^{-1})	g'(L.U.)
$z\,^6F_{1\frac{1}{2}}$	$-0\frac{1}{2}$	−1.06	−0.29	−1.35	2.09	1.056
	$0\frac{1}{2}$	1.06	−0.32	0.74		
$z\,^6F_{0\frac{1}{2}}$	$-0\frac{1}{2}$	0.66	0.29	0.95	−1.29	−0.652
	$0\frac{1}{2}$	−0.66	0.32	−0.34		

The distance between the two atomic levels involved is $d=28.51$ cm^{-1}. The separations d^- and d^+ (see Fig. 1) can be calculated by Eqs. (4)

$$\begin{aligned} d^-&=d+\tfrac{1}{2}ag_{1\frac{1}{2}}-\tfrac{1}{2}ag_{0\frac{1}{2}} \\ d^+&=d-\tfrac{1}{2}ag_{1\frac{1}{2}}+\tfrac{1}{2}ag_{0\frac{1}{2}}. \end{aligned} \tag{4}$$

The g-values, which are in L.U., have been multiplied by a in formulas (4).

The value of a for this experimental case, in which the magnetic field was 85,040 oersteds, is 3.96. Thus we shall have:

$$\begin{aligned} d^-&=28.51+1.98\times1.067-1.98\times(-0.667) \\ &=28.51+2.11+1.32=31.94\ \text{cm}^{-1}. \\ d^+&=28.51-1.98\times1.067+1.98\times(-0.667) \\ &=28.51-2.11-1.32=25.08\ \text{cm}^{-1}. \end{aligned} \tag{5}$$

The large difference existing between the two distances d^- and d^+ should be noted; we expect therefore very different e-values in the two cases.

In a paper on asymmetrical patterns Catalán[3] gives a table with the different possible values for I. For levels $^6F_{1\frac{1}{2}}^{\pm0\frac{1}{2}}$ the value $I^2=2.22$ is given. With this value and those of d^- and d^+, taken from Eq. (5), Eq. (3) gives the values found in Table I.

The perturbed g'-values here obtained are in close agreement with those obtained by experiment, as described in reference 1, in spite of the fact that formula (1) is only a rough approximation. This is shown in Table II.

Evidently the g-values computed *for different fields* will not be equal in cases such as that of $z\,^6F$ of Mn I. The calculated values for this case with a field of 42,520 (half of the value used before) are found in Table III.

A comparison of the resulting values for the two

TABLE IV. Magnetic field (in oersteds).

	Very weak	42520	85040
$z\,^6F_{1\frac{1}{2}}^{\pm1\frac{1}{2}}$	1.067	1.067	1.067
$z\,^6F_{1\frac{1}{2}}^{\pm0\frac{1}{2}}$	1.067	1.056	0.990
$z\,^6F_{0\frac{1}{2}}^{\pm0\frac{1}{2}}$	−0.667	−0.652	−0.591

[3] M. A. Catalán, J. Research Nat. Bur. Stand. (to be published).

different fields, and for a very weak field (Landé value), is given in Table IV.

This comparison clearly shows that, though the changes in g-values on passing from a very weak field to one of about 40,000 oersteds are unimportant, if this value of the field is doubled then the change may, at least in some cases, be of great magnitude.

When one considers that most tables with accurate g-values, published in recent years, have been derived from plates taken at M.I.T., with fields of more than 80,000 oersteds, one is justified in thinking that many of the g-values in such tables may have been altered by interactions. Only by specifying clearly the field used in the observations can such tables have an accurate meaning.

Furthermore, in some extreme cases such as that of $z\,^6F_{1\frac{1}{2}}$ of Mn I, it will be necessary to give separately the g-values for the different magnetic levels. Otherwise what "mean" value can be deduced for an atomic level $z\,^6F_{1\frac{1}{2}}$ of manganese whose two pairs of magnetic levels have, respectively, the g-values 1.067 (for $M=\pm 1\frac{1}{2}$) and 1.003 (for $M=\pm 0\frac{1}{2}$)?

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Apparatus for Low Temperature Study of the Raman Effect*

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A simple modification of a conventional excitation unit for the Raman effect is described that allows study of the effect in liquids at temperatures down to about −150°C. The chief feature of the arrangement is a Dewar-jacketed sleeve that fits around the Raman tube and enables the cooling of the tube by a flow of cold nitrogen gas. By adjustment of the temperature of the gas and its rate of flow, easy and precise control of the temperature of the Raman tube can be obtained. It is also possible to use elevated temperatures (up to +150°C) by heating the nitrogen. The advantages of the system are its simplicity, ease of operation, rapidity of change from low temperature to normal operation, and vice-versa, and the same intensity of illumination as that afforded by room-temperature operation.

EXPERIMENTAL arrangements for the study of the Raman effect at low temperatures have been described many times since 1930.[1] These have nearly always involved surrounding the Raman tube with a Dewar jacket of considerable size, through which the exciting radiation must pass, and have been designed exclusively for use at low temperatures. When we were faced with the problem of low temperature Raman studies, we were forced by circumstance to consider a solution that would permit a rapid interchange of the low temperature set-up with the one used for room-temperature work. It therefore occurred to us to add a low temperature jacket to the Raman tube in such a way that the standard room-temperature set-up could be used unaltered except for the addition of the jacket.

We have constructed this jacket so that it can be readily added to and removed from the standard Raman light furnace used in our Laboratory. In addition to the advantage that this gives us of using the same experimental arrangement for both ordinary and low temperatures, we find that no increase in exposure time is necessary over room-temperature operation. Such an increase is required by some low temperature arrangements because of loss of light occasioned by the walls of the Dewar, the refrigerant or the geometry of the illuminator. Other advantageous characteristics of the present set-up are ease of temperature control and the wide range of temperatures over which operation is possible (−150 to +150°C thus far).

CONSTRUCTION OF THE LOW TEMPERATURE JACKET

The design of the low temperature jacket is dictated mainly by the illuminator in use in our Laboratory. A photograph of this illuminator is shown in Fig. 1.‡ The Raman tube, part of which projects above the illuminator, is located ot the center of a circle of six AH-2 mercury arcs. Between the arcs and the Raman tube is a set of concentric glass cylinders that serve as vessels to hold cooling water and optical-filter solutions. These glass cylinders are sealed into brass plates at top and bottom, the plates being visible in Fig. 1 near the top and bottom of the mercury-arc envelopes.

Figure 2 shows a cross section through the center of the illuminator. The brass plates are labeled "Top Plate of Filter Cylinders" and "Bottom Plate of Filter

* The equipment here described was developed under a program supported by the ONR (Contract N5ori-07810).

† Part of the material in this paper is taken from the thesis submitted by E. Nielsen to the Graduate School of the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, January, 1950.

[1] Compare the summaries in the monographs of Kohlrausch. See also Glockler and Renfrew, Rev. Sci. Inst. 9, 306 (1938).

‡ Reproduced from Harrison, Lord, and Loofbourow, *Practical Spectroscopy* (Prentice-Hall, Inc., New York, 1948), p. 513.

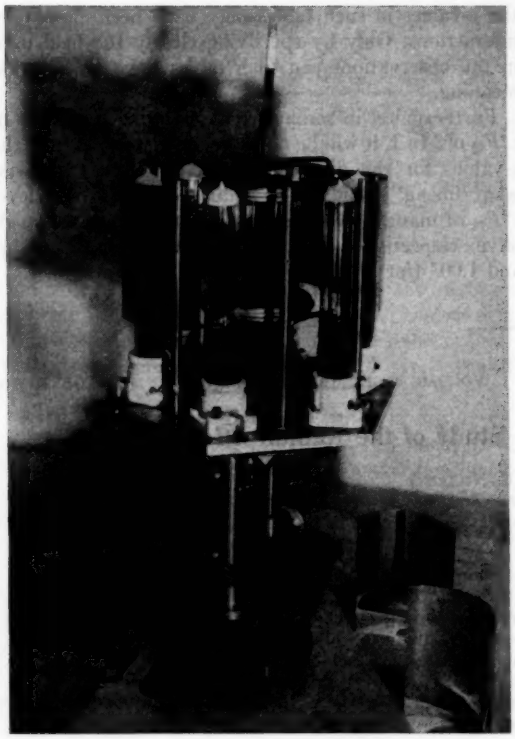

FIG. 1. Excitation unit for the Raman effect. (Reproduced from *Practical Spectroscopy* by courtesy of Prentice-Hall, Inc.)

Cylinders." The innermost of the concentric glass cylinders is also shown in cross section, denoted "Inner-Glass Cylinder." The cooling jacket fits around the Raman tube and cools the tube by a flow of dry nitrogen gas that enters at a temperature near −195°C. The jacket has silvered double walls from the source of cold nitrogen up to the point where it passes through the top brass plate. From that point on, it is single-walled.

The bottom of the jacket is fitted with a compound plug that serves several purposes. A cork ring that fits the jacket tube snug'y holds a brass plug that has a conical surface against which the bottom on the Raman tube rests. Since the axis of this conical surface coincides with the axis of the concentric glass filter cylinders, which in turn is aligned carefully with the optical axis of the spectrograph, the cone automatically centers the window of the Raman tube regardless of the diameter of the latter. The upper part of the Raman tube is aligned by means of a cork stopper.

The bottom of the jacket tube is centered by means of a diametrically split brass ring (see Fig. 2) that rests firmly in the central hole of the lower brass plate. The brass plug for centering the Raman tube fits into the split ring and thereby centers the bottom of the jacket tube as well. The top of the jacket is centered by a conical flare in the wall of the jacket at a point just below the ring-seal where the double-walled part of the jacket ends. This part of the jacket rests in the central hole in the upper brass plate.

The flow of refrigerant gas is as follows: the cold nitrogen strikes the Raman tube at the *T*-junction in the jacket and passes down along the Raman tube until it arrives at the bottom. All the fittings (with the exception of the cork plug) are sufficiently loose to allow a fairly rapid flow of gas. The gas flows down around the Raman tube window into the chamber formed by the hole in the bottom brass plate and the glass window seated therein. The gas then passes through the crack between the two halves of the split ring and up into the space between the jacket tube and the inner glass cylinder. Since the gas is still quite cold, it serves at this point to maintain a considerable temperature difference between the inner glass cylinder, the other side of which is at room temperature, and the jacket tube. It finally escapes to the atmosphere

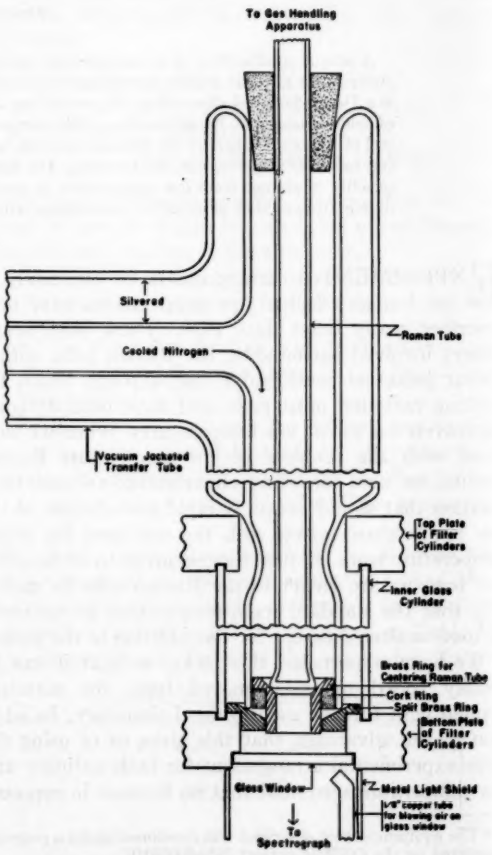

FIG. 2. Cross section of Raman illuminator showing the refrigeration system. The outside diameter of the vacuum-jacketed transfer tube is about 40 mm. The separation of the top and bottom plates of the filter cylinders is 10 cm.

through the loosely plugged hole in the upper brass plate.

Our original design called for the bottom chamber to be shut off from the flow of gas. It was found, however, that after a period of time small traces of water distilled from the chamber onto the Raman-tube window. Experimentation with various procedures to eliminate this trouble led to the design here shown. The fact that the bottom chamber contains cold gas necessitates, of course, some means of forestalling frosting of the outer window. This is easily accomplished by playing a small jet of compressed air from the house supply suitably dried and cleaned of oil onto the outside of the window, as indicated in Fig. 2. With the design here described, no frosting troubles have been encountered in continuous operation at $-120°C$ for periods as long as 30 hours.

Because of the fact that the refrigerating gas warms up as it passes down the Raman tube, the bottom of the tube is warmer than the top. The temperature gradient is of course steeper for the lowest attainable temperatures, and at these temperatures two phenomena are noticeable. If the liquid in the Raman tube has an appreciable vapor pressure at the temperature in use, and if it is in contact only with its own vapor, occasional boiling may occur. This can readily be eliminated by adding an appropriate amount of a non-condensable gas such as nitrogen or helium to the system. Even if there is no bubble formation, the temperature gradient may still give rise to a noticeable turbulence. We have observed this turbulence only at the lower temperatures ($<-100°C$) and have not found it troublesome spectroscopically. It could be eliminated, we believe, by leading in the refrigerant from below, but such a scheme would not be so convenient as the present one.

The source of cold nitrogen is a 50–50 combination of dry tank gas ("oil-pumped" grade) and evaporated liquid nitrogen. The tank nitrogen is cooled to the neighborhood of $-195°C$ by passage through a series of three heat-interchangers like the one shown in cross section in Fig. 3. These also serve to dry the nitrogen and to entrap the resultant frost. The interchangers are immersed in liquid nitrogen in a 10-liter cylindrical Dewar flask, and the output of the last one is mixed with the nitrogen evaporated by the interchange and then fed to the Raman-tube jacket by a double-walled transfer tube. Originally we simply fed nitrogen evaporated by an electrical heater to the jacket, but experience showed that consumption of liquid nitrogen was much slower and control of rate of gas flow much smoother with the system here described.

The consumption of nitrogen depends on the temperature desired. While we have not made careful study of the consumption as a function of attained temperature, we estimate that it requires roughly twice as much refrigerant per unit time to maintain $-150°$ as $-100°$. In the former case the consumption of liquid nitrogen is a little over a liter an hour. This corresponds to a total consumption of about 1250 liters of N_2 gas at standard conditions per hour, since the quantities of tank gas and evaporated liquid nitrogen are roughly equal. With liquid nitrogen at \$0.50 a liter and dry nitrogen at \$3 per cylinder, the refrigeration cost is somewhat under \$1 per hour at the lowest temperatures. A cylinder of nitrogen lasts 8–10 hours, and one filling of the Dewar about the same. The Dewar can be replenished without interruption of the run.

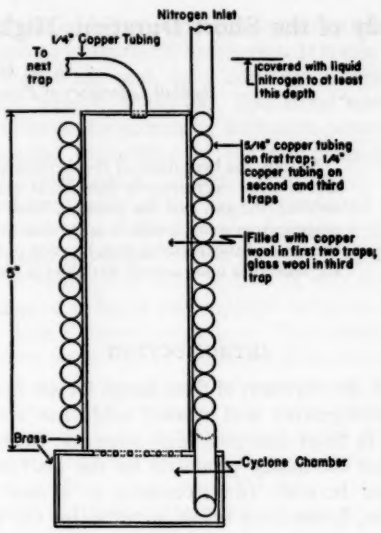
Nitrogen Inlet
1/4" Copper Tubing
To next trap
covered with liquid nitrogen to at least this depth
5/16" copper tubing on first trap; 1/4" copper tubing on second and third traps
Filled with copper wool in first two traps; glass wool in third trap
5"
Brass
Cyclone Chamber
METAL TRAP

FIG. 3. Metal heat-interchanger and trap for refrigeration and drying of nitrogen gas.

Temperatures have been measured in a variety of ways. Thermocouple junctions have been inserted both inside and outside the Raman tube, and the effective temperature of the liquid has also been determined from its vapor pressure. The temperature difference between the Raman tube and the refrigerating gas varied, depending on where it was measured, from 10° to 30°. The temperature gradient along the Raman tube was not measured but was estimated to be about 20°.

A Study of the Short Duration, High Intensity, Electric Arc as a Source of Visible Light

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(Received July 10, 1950)

A study has been made of the dependence of the peak intensity and the duration of the visible light, from arcs of a few microseconds duration in xenon, krypton, and argon, on the input energy, the circuit characteristics, the gas, and the pressure. With input energies up to about 6 joules per discharge, peak currents ranging from a few hundred up to nearly 5000 amperes have been recorded and the relation between the current and the intensity and duration of the light is specified. The dependence of both the current and the arc resistance upon several variables is discussed.

INTRODUCTION

THE development of flash lamps for use in ballistic photography and related fields has stimulated interest in short duration, high intensity, electric arcs. These are commonly produced by the discharge of a condenser between two electrodes in a rare gas atmosphere, breakdown being initiated by the application of a suitable triggering pulse to a third electrode. The intensity of the visible light radiated from the arc column rises rapidly to a maximum, often in a fraction of a microsecond, and then decays somewhat more slowly. A typical oscillogram is reproduced in Fig. 1.

Murphy and Edgerton[1] have reported measurements of peak currents, "tube resistance," and duration of the light in terms of such variables as gap length, capacitance, voltage, and gas pressure for arcs of relatively long duration (20–100 microseconds) using capacitances ranging from several microfarads up to about 60 microfarads.

Craggs and Meek[2] investigated the effect of gap length, gas pressure, and energy dissipation on the intensity of the emitted light for short duration, low current arcs in argon and hydrogen. In their experiments the arc current, taken from a transmission line, consisted of square wave pulses of about 120 amperes lasting for a few microseconds. In the more common short duration arcs resulting from condenser discharge the peak current may be of the order of thousands of amperes.

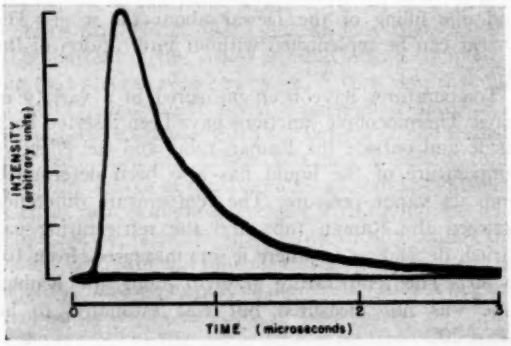

FIG. 1. Variation of light intensity with time. A reproduction of a typical oscillogram.

We have measured the intensity of the visible light, the duration of the light, and the current, for high current arcs of a few microseconds duration as a function of the circuit characteristics, gas, pressure, and input energy in argon, krypton,† and xenon.

EXPERIMENTAL PROCEDURE

All the data reported in this paper were taken from the same discharge tube. The tube was made by sealing two electrodes, spaced 12 millimeters apart, into a Pyrex envelope one inch in diameter. The electrode design was copied from specimens, furnished to this laboratory during the war by E. B. Noel of the Nela Park Laboratory, in which the discharge takes place between special alloy pellets, containing a low work function material, embedded in iron cylinders. These pellets, developed at M.I.T. by Edgerton, Germeshausen, and Grier, reduce electrode sputtering to a minimum and are so effective that after more than a thousand discharges the envelope of our tube showed hardly any sign of sputtering. The tube was evacuated, outgassed in the usual manner, and then filled with a rare gas. In order to reduce to a minimum the self inductance and resistance of the discharge circuit the tube was connected to the condenser by the shortest possible leads of copper strap. The condenser was charged from a d.c. power supply which was isolated from the discharge circuit by a suitable combination of resistances and chokes.

The variation of the light intensity with time was determined by allowing light of all wave-lengths from the arc column to fall on a General Electric PJ—14 photo-cell the output of which was coupled through a video amplifier to the vertical deflection plates of a DuMont 5RP11A cathode-ray tube. The pattern produced on the screen when the output of a fast sweep was simultaneously applied to the horizontal deflection plates was photographed for permanence and for ac-

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[1] P. M. Murphy and H. E. Edgerton, J. App. Phys. 12, 849 (1941).
[2] J. D. Craggs and J. M. Meek, Proc. Roy. Soc. 186, 241 (1946).
† A commercially available mixture consisting of 90 percent krypton and 10 percent xenon.

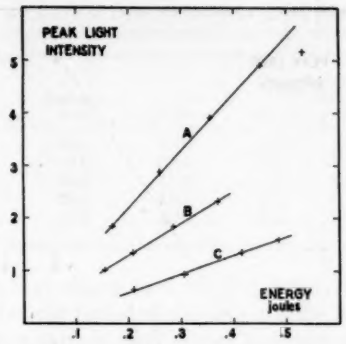

FIG. 2. Dependence of the peak light intensity, for a particular gas, on the energy supplied to the condenser. Curve *A*, xenon at a pressure of 13.7 cm; *B*, krypton at 19 cm pressure; *C*, argon at 29.6 cm pressure.

curacy of measurement. The spectral range utilized was determined by the photo-cell which is reported by the maker to have a response which is nearly uniform from about 4000 to 7000A and relatively small in the adjacent ultraviolet and infra-red regions.

In this type of circuit, information regarding the arc current is commonly obtained by measuring the fall of potential over a resistance inserted into the discharge circuit. However, in view of the difficulties encountered in attempting to obtain a relatively inductance-free, high current resistance of a few tenths of an ohm we have utilized the voltage induced in a small loop of wire very loosely coupled to the discharge circuit to produce on the screen of the oscilloscope a curve showing the rate of change of the current. Information concerning the damping and the frequency of oscillation of the current obtained from such a curve is used to solve the circuit equation for the peak value of the current, the total resistance, and the self-inductance of the circuit.

THE PEAK INTENSITY OF THE LIGHT

The peak intensity of the visible light from the arc is found to be a linear function of the energy supplied to the circuit. This relation is shown in Fig. 2 where the peak intensities are expressed in arbitrary units‡ and the energy was varied by changing only the voltage to which the 0.1 μf condenser was charged. The effect of varying the energy by changing the capacitance as well as the voltage will be discussed later. Because of the differing breakdown voltages for the gases used it was necessary to adjust the pressure by trial until the range of voltages over which the discharge could be readily triggered was approximately the same for each gas. The linearity of peak light intensity with energy exhibited here is evidently quite characteristic of this type of discharge and holds for a very considerable range of arc currents. It was reported by Craggs and Meek[2] for arcs having peak currents of about 120 amperes and has been verified by us with arc currents ranging from a few hundred to almost 5000 amperes. It is also evident in Fig. 2 that the peak light intensity increases with the atomic number of the gas. This is not unexpected in view of both the decreasing ionization potential and the increasing probability of electron collisions with atoms of higher atomic number.[3]

The peak intensity of the light depends not only on the input energy and the atomic number but also upon the particular condenser used in the circuit as shown in Fig. 3. In taking the data plotted in this figure the same range of energies was supplied to the arc§ using each of three different condensers. The limited extent of the curve for the 0.1 μf condenser is due to the onset of spontaneous breakdown at voltages too low to permit the use of energies comparable with those for the larger capacitances. It is evident from the figure that for a given energy the peak intensity is greatest for the condenser of smallest capacitance. We have attempted to interpret this behavior in terms of the arc current since, for large currents, the light intensity is approximately proportional to the current. If the input energy is to be kept constant any increase in capacitance must be accompanied by a decrease in the voltage to which the condenser is charged and the peak current would be expected to remain nearly constant. If however the increase in capacitance is accompanied by an increase in resistance and self-inductance, which may well occur when a large condenser is inserted, then not only may the peak current actually be smaller than before but also the ratio of the energy dissipation in the arc to

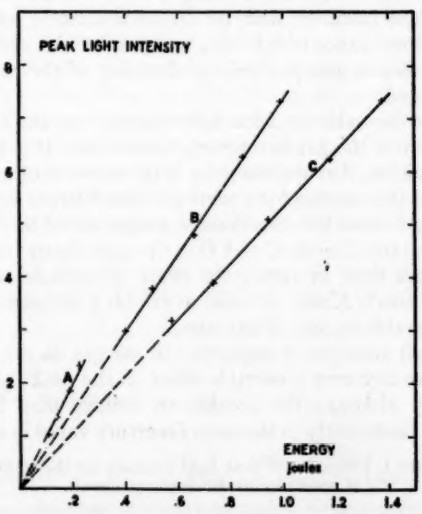

FIG. 3. Peak light intensity *vs.* energy dissipated in the arc, showing the dependence of the intensity on the condenser used. Curve *A*, 0.10 μf; *B*, 0.33 μf; *C*, 0.50 μf condenser.

‡ With an input energy of one joule, in krypton, the peak intensity is estimated to be of the order of 10^{2}–10^{3} candlepower.

[3] R. B. Brode, Rev. Mod. Phys. 5, 257 (1933).

§ The energy supplied to the arc is less than that of the charged condenser by the amount estimated to be dissipated in the condenser itself.

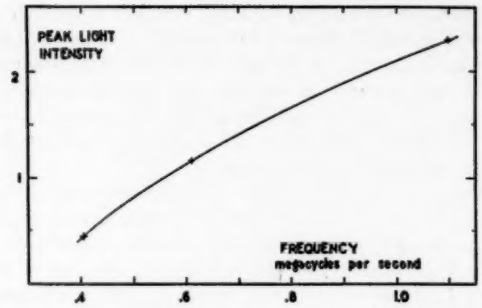

FIG. 4. Peak light intensity as a function of the frequency of oscillation of the arc current. Frequency changed by adding self-inductance to the circuit.

that of the complete circuit may be considerably reduced. Data obtained by adding known quantities of resistance and self-inductance to the discharge circuit bear out these contentions. Figure 4 shows how adding inductance to the circuit reduces the intensity of the light. The highest point on the curve indicates the intensity obtained without loading the circuit with inductance and the two lower points were obtained by adding 0.45 and 1.5 microhenries respectively. From these data the desirability of making the discharge circuit as compact as physically possible and perhaps of using condensers especially designed for minimum self inductance may be appreciated. The addition of resistance to the discharge circuit also strongly reduces the peak light intensity as shown in Table I. For each of the two condensers, charged to the same voltage, the light intensity with no added resistance, with an added resistance of 0.5 ohm, and finally with sufficient resistance to produce critical damping of the current, is quoted.

The dependence of the light intensity on the atomic number of the gas has already been noted. It is found, in addition, that the intensity is to some extent a function of the pressure for a particular gas. Curves *A* and *B* of Fig. 5 show the considerable magnitude of this effect for krypton. Curves *C* and *D* of the same figure indicate however that, in argon, the effect of pressure is relatively small. Xenon is found to exhibit a pressure effect comparable to that of krypton.

Small amounts of impurities in the gas do not seem to have any very noticeable effect on the peak light intensity although the breakdown voltage may be altered, particularly in the case of mercury vapor in argon.

TABLE I. Reduction of peak light intensity by the addition of resistance to the discharge circuit.

Added resistance	Peak light intensity (arbitrary units) with 0.10 μf condenser	with 0.50 μf condenser
none	2.30	5.35
0.50 ohm	1.02	3.05
1.15 ohms		(crit. damp.) 1.98
2.60 ohms	(crit. damp.) 0.62	

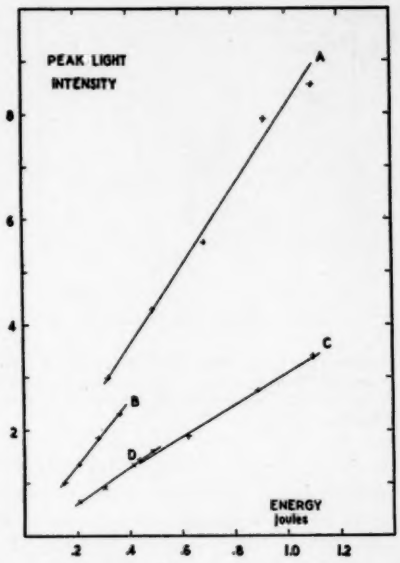

FIG. 5. Peak light intensity *vs.* input energy showing how the intensity, for a particular gas, depends upon the pressure. Curves *A* and *B*, krypton at 40 cm and 19 cm pressure respectively; curves *C* and *D*, argon at 51.3 and 29.6 cm.

However the addition of several centimeters pressure of hydrogen to krypton not only raises the breakdown voltage but for a given energy also appears to increase the visible light output. Other effects produced by the hydrogen will be discussed shortly.

DURATION OF THE LIGHT

We have arbitrarily defined the duration of the visible light from the arc as the difference of the times at which the intensity of the light is twenty percent of the maximum value. These times are determined from oscillograms, such as the one reproduced in Fig. 1 by the use of a measuring microscope and some of them are listed in Table II. It appears that neither the kind of rare gas used nor the pressure over a considerable range affects the duration time very noticeably although the addition of several centimeters of hydrogen tends to quench the afterglow, as found by McCormick, Madansky and Fairbanks[4] in another type of discharge tube, and so shortens the duration time somewhat. The data of Table II indicate clearly that the duration time of the visible light is primarily a function of the circuit characteristics which, in our experiments, are in no small measure determined by the inherent self-inductance and resistance of the condenser as well as by its capacitance. Thus the durations listed in the table are characteristic of the particular Pyranol condensers which we used rather than of their capacitance alone and, since the self-inductances of these condensers were not meas-

[4] W. W. McCormick, L. Madansky, and A. F. Fairbanks, J. App. Phys. **19**, 221 (1948).

TABLE II. Duration times for different gases, pressures, and condensers at approximately constant voltage.

Gas	Pressure (cm)	Volts	Duration (microseconds) with capacitance of 0.1 μf	0.33 μf	0.50 μf
Xenon	13.7	3000	1.16	1.66	2.08
Krypton	19.0	2960	1.04	1.78	2.28
Krypton	40.0	3130	1.17	1.80	2.09
Argon	29.6	3210	1.07	1.79	2.00
Argon	51.3	2960	1.17	1.86	1.92

ured, we have chosen to plot in Fig. 6 the duration as a function of the period of oscillation of the arc current. The points marked with circles represent averages of numerous data taken with the 0.1, 0.33, and 0.50 μf condensers while the points marked with squares are the result of inserting additional self-inductance into the circuit.

Oscillograms show that the variation of the total light intensity with time is closely related to that of the arc current. It is to be expected then that any change in circuit characteristics which tends to prolong the period of current flow may increase the duration of the light. The addition of inductance seems to produce such an effect by decreasing the frequency of the current oscillations and also reduces the damping so that considerable fluctuations may appear in the decay curve of the light intensity at times corresponding to current maxima. The addition of resistance to the circuit tends to damp out these fluctuations without, however, appreciably affecting the duration as we have defined it.¶

Finally, very little dependence of the duration on the voltage to which the condenser is charged and therefore on the input energy is found. This is shown in Table III where durations are specified for discharges in argon over a considerable range of voltages using the 0.33 μf condenser. The gas pressures were chosen to avoid spontaneous breakdown and allow the discharge to be conveniently initiated by triggering. The durations are seen to scatter about an average value of 1.80 microseconds. This scattering is rather typical of the data for xenon and krypton also. In general, changes of a factor of two in the voltage and therefore a fourfold energy change seem to produce no very conclusive evidence of change in the duration of the light. This is in accord with the foregoing analysis which correlates the duration primarily with the frequency of the current oscillation, since merely raising the condenser voltage leaves the frequency unchanged.

THE PEAK CURRENT

In contrast to the linear damping commonly associated with certain types of spectroscopic spark sources

¶ At intensities below the 20 percent points which we have used irregularities in the decay curve may have a considerable effect on the measured duration time.

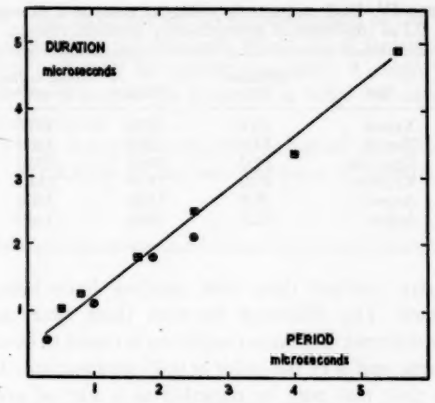

FIG. 6. Duration of the light as a function of the period of oscillation of the arc current.

in air[5] we have found the damping in our circuits to be exponential in every case. The circuit has therefore been treated as an equivalent R, C, L type and the differential equation solved for values of the first maximum (peak value) of the current, the magnitude of the total resistance, and the total self-inductance using the values of the damping factor and the oscillation frequency obtained from oscillograms of the current rate of change. Table IV lists some values of the peak current for different gases and pressures using the 0.1 μf condenser charged to about the same initial voltage for each of the gas fillings listed in the table. It is readily seen that the currents do not differ much from one gas to another nor are they much affected by considerable changes in pressure in the same gas. It appears then that for a given discharge circuit the peak current depends primarily on the voltage to which the condenser is charged. This dependence is illustrated by the data of Table V where peak currents corresponding to a number of voltages between 2500 and 5000 are listed for four different condensers.

The times at which both the current and the light

TABLE III. Duration times for a considerable range of voltages using the 0.33μf condenser. Pressure adjusted for satisfactory initiation of the arc.

	17.1 cm of argon			
Volts	1470	1800	2135	
Duration (microseconds)	1.82	1.80	1.71	
	29.6 cm of argon			
Volts	2040	2460	2880	3150
Duration	1.82	1.77	1.82	1.79
	51.3 cm of argon			
Volts	2960	3540	4210	4780
Duration	1.86	1.82	1.80	1.80

Average duration 1.80 microseconds

[5] J. H. Enns and R. A. Wolfe, Special Technical Publication No. 76, American Society for Testing Materials.

TABLE IV. Peak currents for different gases and pressures. 0.1 μf condenser at approximately constant voltage.

Gas	Pressure (cm)	Volts	Peak current (amperes)
Xenon	10.9	2820	1570
Xenon	13.7	3000	1480
Krypton	19.0	2960	1530
Krypton	40.0	3130	1540
Argon	29.6	3120	1600
Argon	51.3	2960	1450

intensity reached their first maxima have been determined. The difference between these times under many different discharge conditions is found to be about the same and is of the order of 0.05 microsecond. It appears that this may be regarded as a sort of average time lag, evaluated at peak values of current and light intensity, between absorption of electrical energy and the subsequent radiation of a portion of the energy as visible light.

THE ARC RESISTANCE

For each set of conditions the total resistance of the discharge circuit was found by solving the circuit equation as described above. The fraction of this total to be assigned to the arc was then found by subtracting the equivalent resistance of the condenser measured by a Q meter. While this procedure does not furnish very accurate values of the arc resistance due to the considerable uncertainty in measurement of the condenser resistance we have chosen it rather than the alternative one of attempting to measure the arc voltage on account of the rather high frequencies and the very intense magnetic fields present. The arc resistance is found to vary inversely as the voltage to which the condenser is charged. Thus the increase in energy associated with the higher voltage results not only in a larger current as we have previously observed but also, as might be expected, in lower resistance in the arc. This together with the reduction in arc resistance at lower gas pressures is shown in Fig. 7 where curves are plotted for three different pressures of the krypton mixture. In contrast to the pressure effect shown in this figure the arc resistance is found to be rather insensitive to the particular gas used.

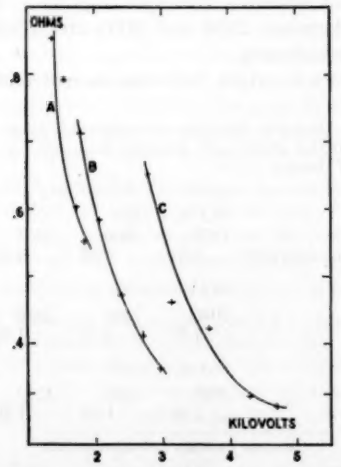

FIG. 7. Arc resistance, in krypton, as a function of the initial voltage of the condenser and of the pressure of the gas. Curve A, 10.6 cm; B, 19.0 cm; C, 40 cm pressure.

TABLE V. Dependence of the peak current on the condenser and the voltage to which it is charged. Krypton at a pressure of 40 cm.

Volts	Peak current (amperes) with condenser of capacitance 0.01 μf	0.1 μf	0.33 μf	0.50 μf
2550	250	1130	2120	2400
3130	380	1540	2690	2980
3710	540	1900	3300	3550
4290	735	2270	3810	4150
4700	845	2550	4180	4600

Since the energy supplied to the circuit may be increased not only by raising the voltage but also by increasing the capacitance at constant voltage it might be expected that the arc resistance would be an inverse function of the capacitance. This expectation is confirmed by our data and was found also by Murphy and Edgerton[1] for much larger capacitances than we have used. It is interesting to note that Murphy and Edgerton, using about the same argon pressure and peak currents as were used in this research, found values for the arc resistance of the same order of magnitude as we have obtained even though they used much longer discharge tubes and worked at much lower frequencies.

SUMMARY

We have found that the peak intensity of the visible light increases linearly with the input energy and, for a given energy, is likely to be largest for a condenser of small capacitance charged to a high voltage. The peak intensity is found to be highest for discharges in xenon, then in krypton, and then, at a considerably lower level, in argon. A considerable increase in intensity with increasing pressure was observed in xenon and krypton.

The duration of the light is found to be approximately a linear function of the period of oscillation of the arc current and to depend very little on the gas or the pressure.

The addition of self-inductance to the circuit affects adversely both the peak intensity and the duration of the light while the addition of resistance reduces only the peak intensity, leaving the duration relatively unchanged.

The peak current in the arc appears to be nearly inde-

pendent of the gas and the pressure but is a function of the discharge circuit characteristics and of the voltage to which the condenser is charged.

The resistance of the arc varies inversely as the voltage and is also an inverse function of the capacitance. It is larger at the higher pressures but depends very little on the particular gas used.

Our experiments have dealt only with the total visible light from the arc. A determination of the spectral distribution of the light would be of considerable interest and may be undertaken later. A cursory examination indicates the presence of both line and continuous spectra.

We wish to express our appreciation of the assistance of R. W. Kebler on various problems of instrumentation.

Photometric and Electrical Units Established by Law

The 81st Congress has approved, on July 21, 1950, Public Law 617 so as to give formal and legal status to photometric and electrical units. This legislation was sponsored by the National Bureau of Standards and resulted from research by the Bureau. While the units defined are largely electrical rather than optical there should be an interest in both electrical and optical terms by members of the Optical Society and hence all units in the new law have been included in this note. The changes in magnitude of the units are small, in no case larger than one-twentieth of one percent, but the new law puts the values on a clear and unambiguous basis which assures the closest practicable agreement between electrical and mechanical units.

The law previously in effect, enacted 56 years ago, included double definitions of the units. There were no central standards laboratories at that time, and to enable any competent laboratory to set up valid electrical standards the United States law, as well as international agreements, prescribed certain devices to produce three basic units. The ampere was defined by the rate of deposition of silver in a voltameter or coulometer, the ohm as the resistance of a specified column of mercury, and the volt as a specified fraction of the electromotive force of a certain type of standard cell.

It was later found that these conventional standards did not produce exactly the intended values of the units. Technical and scientific developments, including the use of electrical instruments for many kinds of measurement, made it increasingly inconvenient to have electrical units not strictly consistent with those of mechanics. Furthermore national standards laboratories were established in all of the larger industrial countries. These laboratories maintain the basic standards of measurement so that the need for the old system of reproducible electrical standards has disappeared.

Recognizing these changed conditions, the American Institute of Electrical Engineers in 1928 proposed a return to the basic "absolute" units. Twenty years of research and negotiation were required to bring about unanimous international action to this end in which the National Bureau of Standards played a leading role. The story of this accomplishment is told in detail in NBS Circular 475, "Establishment and Maintenance of the Electrical Units" (Superintendent of Documents, Government Printing Office, Washington 25, D. C., 25 cents per copy).

The new Act is similar to the old law in defining the fundamental practical units as multiples of the units of the centimeter-gram-second electromagnetic system. In fact, however, they are also component parts of the meter-kilogram-second system which is being widely accepted in textbooks and in engineering practice. Two sections of the Act define the basic photometric units, the candle and the lumen, which were not previously defined by law.

The provisions of the law are as follows:

That from and after the date this Act is approved, the legal units of electrical and photometric measurement in the United States of America shall be those defined and established as provided in the following sections.

SEC. 2. The unit of electrical resistance shall be the ohm, which is equal to one thousand million units of resistance of the centimeter-gram-second system of electromagnetic units.

SEC. 3. The unit of electric current shall be the ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electromagnetic units.

SEC. 4. The unit of electromotive force and of electric potential shall be the volt, which is the electromotive force that, steadily applied to a conductor whose resistance is one ohm, will produce a current of one ampere.

SEC. 5. The unit of electric quantity shall be the coulomb, which is the quantity of electricity transferred by a current of one ampere in one second.

SEC. 6. The unit of electrical capacitance shall be the farad, which is the capacitance of a capacitor that is charged to a potential of one volt by one coulomb of electricity.

SEC. 7. The unit of electrical inductance shall be the henry, which is the inductance in a circuit such that an electromotive force of one volt is induced in the circuit by variation of an inducing current at the rate of one ampere per second.

SEC. 8. The unit of power shall be the watt, which is equal to ten million units of power in the centimeter-gram-second system, and which is the power required to cause an unvarying current of one ampere to flow between points differing in potential by one volt.

SEC. 9. The units of energy shall be (a) the joule, which is equivalent to the energy supplied by a power of one watt operating for one second, and (b) the kilowatt-hour, which is equivalent to the energy supplied by a power of one thousand watts operating for one hour.

SEC. 10. The unit of intensity of light shall be the candle, which is one-sixtieth of the intensity of one square centimeter of a perfect radiator, known as a "black body," when operated at the temperature of freezing platinum.

SEC. 11. The unit of flux of light shall be the lumen, which is the flux in a unit of solid angle from a source of which the intensity is one candle.

SEC. 12. It shall be the duty of the Secretary of Commerce to establish the values of the primary electric and photometric units in absolute measure, and the legal values for these units shall be those represented by, or derived from, national reference standards maintained by the Department of Commerce.

SEC. 13. The Act of July 12, 1894 (Public Law Numbered 105, Fifty-third Congress), entitled "An Act to define and establish the units of electrical measure," is hereby repealed.

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Diffraction Pattern Deterioration by Roof Prisms*

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(Received January 11, 1950)

A description is given of the manner in which two and three internal reflection roof prisms bring about a deterioration in the diffraction pattern form. Assuming a rectangular limiting aperture, the deterioration consists of a doubling of the diffraction pattern in a direction perpendicular to the roof edge. Parallel to the roof edge no deterioration of the diffraction pattern takes place so that in this direction it is always of the Fraunhofer form. If plane polarized light is allowed to enter these prisms, the form of the doubling in a direction perpendicular to the roof edge can be changed by rotating the incident azimuth angle of the entering plane polarized light. Usually such a doubling of the diffraction pattern is associated with an error in the roof angle of the prism. The theory presented both in this paper and the previous paper predicts a doubling of the diffraction pattern in a direction perpendicular to the roof edge even for a prism with a perfect 90° roof angle. As compared with the earlier paper on this same subject, the theory presented in this paper is considerably simplified so that for prisms with uncoated reflecting surfaces the diffraction pattern form can now be calculated for a two or three internal reflection roof prism from a knowledge only of the *angular deviation at the roof edge*, the prism *refractive index*, and the *entering azimuth angle* of the plane polarized light if the prism is illuminated with plane polarized light. Experimentally it was found that silvering the roof surfaces for two different forms of prisms decreased the doubling of the diffraction pattern in a direction perpendicular to the roof edge. The theory presented in this paper makes it possible to calculate also the diffraction pattern forms for roof prisms with coated reflecting surfaces providing the *refractive index* and *absorption index* of the coating material are known. In this paper the theory will be carefully tested on the 90° deviation Amici roof prism by comparing the microphotometer tracings of the photographed diffraction patterns with those to be expected from the theory. Several conclusions about the forms of the diffraction patterns for roof prisms having a wide range in geometry will be presented both when these prisms have coated and uncoated reflecting roof surfaces.

1. INTRODUCTION

IN a previous paper[1] on this general subject, a description was given of some anomalies in the Fraunhofer diffraction pattern which occurred when parallel light passed through a small rather odd-shaped perfectly made three internal reflection roof prism and was brought to a focus by a lens. With unpolarized incident light, these anomalies consisted of a doubling of the diffraction pattern in a direction perpendicular to the roof edge while parallel to the roof edge the diffraction pattern was of the usual Fraunhofer form associated with square apertures. If plane polarized light was allowed to enter the prism, the form of the doubling in a direction perpendicular to the roof edge could be changed by rotating the incident azimuth angle of the entering plane polarized light. The form of the diffraction pattern parallel to the roof edge, however, was independent of the entering azimuth of the plane polarized light and remained of the Fraunhofer form. Previous to this paper and another paper[2] by Joos, it was always assumed that an angular doubling of this sort for all types of roof prisms was the result of an error in the 90° roof angle. Attempts were made to minimize this doubling by increasing the accuracy of the roof angle on these prisms, but this did not help. When, however, the roof surfaces were silvered,† an apparently bad roof prism was transformed into a good prism with very small angular doubling. In the earlier paper[1] attempting to explain this peculiar behavior, a theoretical treatment of the problem was given showing that for a roof prism with uncoated reflecting roof surfaces having no wedge angle error and a perfect 90° roof angle a doubling of the diffraction pattern in a direction perpendicular to the roof edge could be expected both for polarized and unpolarized light, the magnitude of the doubling being a complex function of the geometry of the prism and its refractive index. Rather long formulas were developed making it possible to calculate the forms of these patterns. The calculated forms resembled those obtained experimentally.

In fairness to the earlier somewhat introductory paper[1] on this subject, it should be stated that all the essential equations are present in that paper for calculating the diffraction pattern form for a two or a three internal reflection roof prism with uncoated reflecting surfaces when the prism is illuminated with either polarized or unpolarized light. That paper, however, was written in a very generalized form which made it necessary to make a complete investigation of the geometry of each prism, its associated rays, and the various directions of the perpendicular and parallel components of the electric vector at each reflecting surface before the diffraction pattern forms could be calculated. To obtain more simplified equations, it was necessary to make some rather long mathematical expansions. This was tried at the time of the writing of the earlier paper but due to their complexity and other more pressing problems, sufficient time was not available. These expansions have since been completed and the numerical results checked with the results on the three internal reflection prism described in the earlier paper.

Roof prisms have been used quite frequently in the

* Paper presented in part at the New York meeting of the Optical Society of America, March, 1948.
** Now Resident Naval Inspector of Ordnance at Arma Corporation, Brooklyn 32, N. Y.
[1] A. I. Mahan, J. Opt. Soc. Am. 35, 623 (1945).
[2] G. Joos, Zeiss Nachrichten 4, 9 (1943).
† First suggested by Max Zwillinger of the Optics Laboratory of the Naval Gun Factory in January, 1943.

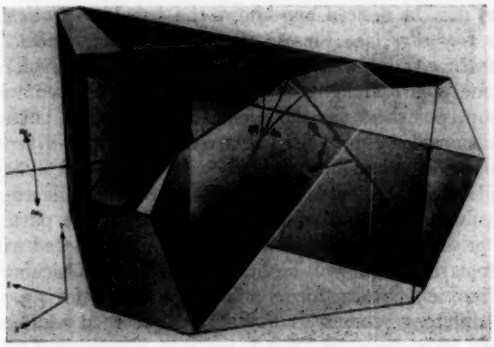


FIG. 1. Three-dimensional ray diagram for a 90° deviation Amici roof prism.

design of optical instruments and are of many forms. One of the simplest and most common forms is the 90° deviation Amici roof prism shown in the three-dimensional diagram in Fig. 1. In this diagram a plane polarized light ray whose electric vector is indicated by A_0 is incident normally on the first surface of the prism in the upper half of its aperture and follows the indicated path before emerging from the lower half of the aperture. Its entering azimuth angle α is measured as indicated with respect to the perpendicular component of the electric vector at the first roof surface. At each point of incidence on the two roof surfaces, an attempt has been made to indicate the positive directions of the perpendicular and parallel components of the electric vector. The planes of incidence at these two roof surfaces (determined by incident ray and surface normal) have also been indicated by shading. The frame of reference to be used later in this paper is shown at the lower left. It is the angle between the two roof surfaces at the right which must be as nearly 90° as possible if the prism is to function satisfactorily. If this angle deviates from 90°, a geometrical angular doubling of the image will appear in the system in which the prism is used. In Fig. 2 a two-dimensional top view of Fig. 1 is shown again with the entering ray normal to the first prism surface. The function of such a prism when used with telescopic systems is that of deviating parallel bundles of rays through 90° and inverting the images of distant objects both up and down and left and right. Other forms of roof prisms can quite readily be imagined from Fig. 2 for which the angular deviations are different (see Fig. 4) or the number of internal reflections larger. Some of the other better known forms of roof prisms are the Abbe, Springer, Hensoldt and Wirth prisms.

In making all roof prisms, the most difficult part is that of making the roof angle as nearly 90° as possible to avoid the previously mentioned geometrical doubling of the image. In checking the magnitude of the image doubling produced by roof angle errors, collimators and high power telescopes (of the order of thirty or greater) are used. If there is an easily perceptible angular doubling of the image in a direction perpendicular to the roof edge for a 90° deviation Amici roof prism, this error can be correctly associated with a geometrical error in this roof angle. However, when the square aperture of such a perfectly made Amici roof prism having no roof angle error and no wedge angle error is stopped down sufficiently so that diffraction effects begin to appear, one finds both theoretically and experimentally that the Amici roof prism also shows the same types of diffraction pattern anomalies as found in the earlier prism but their magnitudes are much reduced. Thus in a direction parallel to the roof edge, the diffraction pattern is always of the classical Fraunhofer form (see Fig. 9) while perpendicular to the roof edge its form becomes a function of whether the prism is illuminated with polarized or unpolarized light. If the roof surfaces are coated with silver the form of the pattern in a direction perpendicular to the roof edge is again changed, its form again depending upon whether the prism is illuminated with unpolarized light (see Fig. 12) or plane polarized light. A perfectly made roof prism would, therefore, be expected to show different resolving powers in the two directions and, hence, bring about a resulting deterioration of the image. To make this deterioration as small as possible, the form of the diffraction pattern in a direction perpendicular to the roof edge should be made to approach as nearly as possible the classical Fraunhofer pattern. To make this possible, one must understand the underlying factors contributing to the form of the diffraction pattern and how they may be controlled.

The theory which is given in the present paper will be concerned only with plane monochromatic light waves whose wave fronts are perpendicular to the incident ray drawn in Fig. 2. The prisms also will be assumed to be perfectly made and hence to be free from

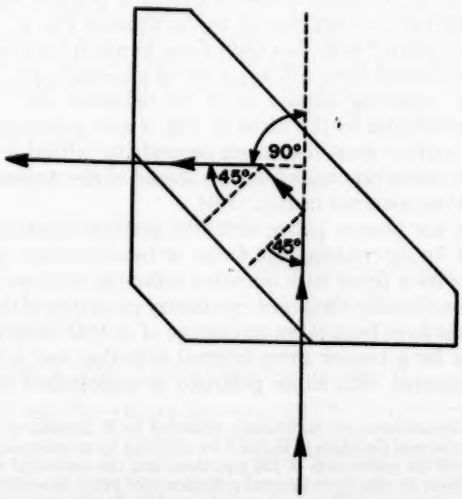


FIG. 2. Ray diagram for 90° deviation Amici roof prism.

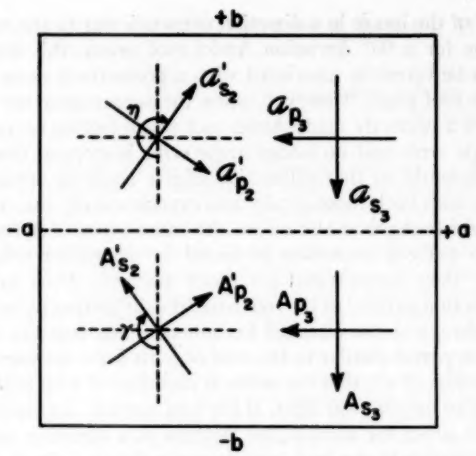


FIG. 3. Directions of vibration of the perpendicular and parallel components of the electric vector at the two second reflecting roof surfaces for a 90° deviation Amici roof prism and the final directions about which they were resolved in the emerging aperture of the prism.

the previously mentioned geometrical errors. If, therefore, the focusing lens has its axis parallel to the emerging ray drawn in Fig. 2 and a square aperture is the limiting aperture, the diffraction pattern form which is determined by the theory in the present paper is rigorously only that on the axis of the focusing lens. As will be seen later from the more general discussion of the problem which follows, the theory can be extended quite readily (assuming off axis lens errors do not contribute to the form of the pattern) to other plane waves whose rays are still in the plane or are parallel to the plane of Fig. 2 by applying Snell's Law at the entering and leaving surfaces of the prism and considering the prism to have a different geometry (see Fig. 4), but it cannot in its present form be extended to plane waves whose rays are not parallel to the plane of Fig. 2. The three internal reflection roof prisms to which the theory in its present form will apply are of a special type. The third reflecting surface must be uncoated and also perpendicular to the plane of Fig. 2 and reflection at this surface must take place beyond the critical angle (this limitation comes from the second of the symmetry relations assumed in Eqs. (19)).

In the present paper, first, the previous equations‡ used for determining the forms of the diffraction patterns for a prism with uncoated reflecting surfaces will be considerably simplified. Symmetry properties of these prisms have been taken advantage of so that computations for a two or three internal reflection roof prism illuminated with either polarized or unpolarized light can now be done if one knows the *angular deviation at the roof edge* (see Fig. 4) for the particular prism, its *refractive index*, and the *entering azimuth angle* of the plane polarized light if the prism is illuminated with plane polarized light. Calculated diffraction pattern forms will be presented for roof prisms of *different geometries* when illuminated with unpolarized light and having uncoated roof surfaces. Second, the effect of silvering the roof surfaces on the diffraction pattern of prisms of different geometries when illuminated with unpolarized light will be briefly considered. Calculated diffraction pattern forms will be presented for prisms of different geometries having silver coated roof surfaces when they are illuminated with unpolarized light so that the change in the diffraction pattern form resulting from silvering can be seen. Third, these equations will be applied to the 90° deviation Amici roof prism (see Figs. 1 and 2) having both uncoated and silver coated reflecting roof surfaces and a careful comparison will be made between the forms of the theoretically calculated patterns and those obtained by microphotometering the experimentally photographed diffraction patterns.

2. POLARIZATION PROPERTIES FOR ROOF PRISMS WITH UNCOATED REFLECTING ROOF SURFACES

In determining the polarization properties for roof prisms of the Amici type having uncoated roof surfaces, the same formulas derived previously are used with minor modifications. As was done in the earlier paper, the 90° deviation Amici prism also can be considered to be divided into upper and lower halves by a horizontal plane intersecting the roof edge (see Fig. 1). If now a plane polarized monochromatic light wave is allowed to be incident upon the prism in the direction indicated in Fig. 2, it may travel by one of two paths. Either it may enter the upper half of the prism aperture and emerge from the lower (see Fig. 1), or it may enter the lower half of the aperture and emerge from the upper. In either case it should be clear from the geometry of the prism that the path in glass for a perfectly made prism must be the same for the two directions. In general, therefore, it might be expected that the emergent waves in both halves of the aperture would have the same amplitude and phase. Actually if one places a polarizer and analyzer in front and in back of an Amici roof prism having uncoated roof surfaces, one finds that the waves emerging from the two halves of the aperture do not have the same amplitude and phase but are each elliptically polarized, the ellipticity in the two halves of the aperture in general being different for each position of the polarizer. This difference in ellipticity as was seen in the earlier paper is brought about by the phase changes upon reflection at the glass-air roof surfaces (the angle of incidence being greater than the critical angle) and the peculiar geometry of the perpendicular and parallel components of the

‡ The authors are particularly indebted to F. Zernike of the University of Grönigen in Holland for checking by an independent method the correctness of the equations and the numerical substitutions for the three internal reflection roof prism described in the earlier paper. This work was done while Zernike was at the Johns Hopkins University in Baltimore.

electric vector in the two halves of the prisms (see Fig. 3).

It will not be the purpose of this paper to rederive the rather long expressions in the earlier paper but rather to continue their development and to simplify them. For details of the derivation of the equations immediately following, it is suggested that the earlier paper[1] be consulted. By way of a brief review, the following remarks can be made to indicate how the expressions for the electric vectors of the four emergent plane waves in the upper and lower halves of the aperture (see Fig. 3) were arrived at. An incident plane polarized monochromatic light wave with an electric vector written as $A_0 \sin(\omega t + d_i)$ was assumed to enter the upper half of the prism aperture as suggested in Fig. 1. For simplicity reflection losses at the entering and leaving faces and absorption losses in the prism were neglected. This wave was assumed to be polarized at an azimuth angle α measured in a counterclockwise direction from the positive direction§ of the "s" component at the upper roof surface when looking along the path of the light. At this surface, the incident electric vector was decomposed into "s" and "p" components A_{s1} and A_{p1}. These two waves after reflection were designated by A_{s1}' and A_{p1}', the difference between these and the previous two incident waves being that the phase changes after reflection for the two components have been added to the phase d_i of the incident wave. It is not necessary for a roof prism having uncoated roof surfaces to consider reflection losses at these surfaces since for incidence beyond the critical angle at a glass-air reflecting surface, the reflectance for both the "s" and "p" components is unity. These reflected waves are then incident upon the lower roof surface whose "s" component forms an angle β with the "s" component of the upper roof surface. To determine the additional polarization properties contributed by this roof surface, the electric vectors of the two waves reflected from the upper roof surface must be resolved about the directions of the "s" and "p" components for the lower roof surface. The electric vectors of these two waves were designated by A_{s2} and A_{p2}. If again the phase changes after reflection for the "s" and "p" components are added to the phases of the two incident waves upon the lower roof surface, the two waves after reflection (again assuming a reflectance of unity for both components) were written as A_{s2}' and A_{p2}'. Assuming the same plane polarized monochromatic light wave is simultaneously incident upon the lower half of the prism aperture, one can by an identical procedure write down expressions for the electric vectors of the two emergent plane polarized waves resolved about the directions of the "s" and "p" components at the upper roof surface for light traveling the second path through the prism and emerging from the upper half of the prism aperture. These electric vectors in the earlier paper were designated as $\mathfrak{A}_{s2}'$ and $\mathfrak{A}_{p2}'$. The equations for these two waves are identical in form with A_{s2}' and A_{p2}' with the exception that α and β are everywhere replaced by δ and ϵ, the corresponding azimuth angles for light entering the lower half of the prism aperture and emerging from the upper. If now one looks into the emergent aperture of a 90° deviation roof prism of the Amici type in a direction opposite to the emergent light in Fig. 2, the positive directions of vibration of the "s" and "p" components in the two halves of the aperture after reflection at each of the last two reflecting roof surfaces will be as shown at the left in Fig. 3. Before these four waves can be combined in the focal plane of the focusing lens, they must be further resolved about a common set of axes chosen for convenience here as the horizontal and vertical directions suggested at the right in Fig. 3. Such a choice as can be seen in the earlier paper makes it possible to apply these equations also to three internal reflection roof prisms whose third reflecting surface is parallel to A_{s3} and $\mathfrak{A}_{s3}$ and on which reflection occurs beyond the critical angle. If as indicated in Fig. 3, the angle between A_{s3} and A_{s2}' is γ, then the two emergent waves A_{s3} and A_{p3} when resolved about the horizontal and vertical directions can be written in the following forms as indicated in the previous paper:

$$A_{s3} = A_0\{\cos^2\alpha(\cos^2\beta\cos^2\gamma+\sin^2\beta\sin^2\gamma)+\sin^2\alpha(\sin^2\beta\cos^2\gamma+\cos^2\beta\sin^2\gamma)$$
$$-\tfrac{1}{2}\sin2\alpha\sin2\beta\cos2\gamma\cos(d_{s1}-d_{p1})-\sin2\gamma[\cos^2\alpha\cos^2\beta+\sin^2\alpha\sin^2\beta-\tfrac{1}{2}\sin2\alpha\sin2\beta\cos(d_{s1}-d_{p1})]^{\frac{1}{2}}$$
$$\cdot[\cos^2\alpha\sin^2\beta+\sin^2\alpha\cos^2\beta+\tfrac{1}{2}\sin2\alpha\sin2\beta\cos(d_{s1}-d_{p1})]^{\frac{1}{2}}\cdot\cos[(R_{s2}-R_{p2})+(d_{s2}-d_{p2})]\}^{\frac{1}{2}}$$
$$\cdot\sin(\omega t+d_i+d_o+R_{s3}), \quad (1)$$

$$A_{p3} = A_0\{\cos^2\alpha(\cos^2\beta\sin^2\gamma+\sin^2\beta\cos^2\gamma)+\sin^2\alpha(\sin^2\beta\sin^2\gamma+\cos^2\beta\cos^2\gamma)$$
$$+\tfrac{1}{2}\sin2\alpha\sin2\beta\cos2\gamma\cos(d_{s1}-d_{p1})+\sin2\gamma[\cos^2\alpha\cos^2\beta+\sin^2\alpha\sin^2\beta-\tfrac{1}{2}\sin2\alpha\sin2\beta\cos(d_{s1}-d_{p1})]^{\frac{1}{2}}$$
$$\cdot[\cos^2\alpha\sin^2\beta+\sin^2\alpha\cos^2\beta+\tfrac{1}{2}\sin2\alpha\sin2\beta\cos(d_{s1}-d_{p1})]^{\frac{1}{2}}\cdot\cos[(R_{s2}-R_{p2})+(d_{s2}-d_{p2})]\}^{\frac{1}{2}}$$
$$\cdot\sin(\omega t+d_i+d_o+R_{p3}). \quad (2)$$

§ At each reflecting roof surface, the positive direction of the "p" component is chosen in the direction of the inward surface normal. The positive direction of the "s" is then chosen 90° clockwise from "p" when looking along the path of the light.

In the above expressions d_{s1}, d_{s2}, d_{p1}, and d_{p2} are the phase changes after reflection for the "s" and "p" components of the electric vector at each roof surface and d_g is the increase in phase of the waves due to passage through the glass. R_{s2}, R_{p2}, R_{s3}, and R_{p3} are defined by the following relations

$$\tan R_{s2}=\frac{\cos\alpha\cos\beta\sin d_{s1}-\sin\alpha\sin\beta\sin d_{p1}}{\cos\alpha\cos\beta\cos d_{s1}-\sin\alpha\sin\beta\cos d_{p1}}, \tag{3}$$

$$\tan R_{p2}=\frac{\cos\alpha\sin\beta\sin d_{s1}+\sin\alpha\cos\beta\sin d_{p1}}{\cos\alpha\sin\beta\cos d_{s1}+\sin\alpha\cos\beta\cos d_{p1}}, \tag{4}$$

$$\tan R_{s3}=\frac{C\sin(R_{s2}+d_{s2})-D\sin(R_{p2}+d_{p2})}{C\cos(R_{s2}+d_{s2})-D\cos(R_{p2}+d_{p2})}, \tag{5}$$

$$\tan R_{p3}=\frac{E\sin(R_{s2}+d_{s2})+F\sin(R_{p2}+d_{p2})}{E\cos(R_{s2}+d_{s2})+F\cos(R_{p2}+d_{p2})}. \tag{6}$$

In these relations C, D, E, and F are given by

$$C=\cos\gamma\{\cos^2\alpha\cos^2\beta+\sin^2\alpha\sin^2\beta-\tfrac{1}{2}\sin 2\alpha\sin 2\beta\cos(d_{s1}-d_{p1})\}^{\frac{1}{2}}, \tag{7}$$

$$D=\sin\gamma\{\cos^2\alpha\sin^2\beta+\sin^2\alpha\cos^2\beta+\tfrac{1}{2}\sin 2\alpha\sin 2\beta\cos(d_{s1}-d_{p1})\}^{\frac{1}{2}}, \tag{8}$$

$$E=\sin\gamma\{\cos^2\alpha\cos^2\beta+\sin^2\alpha\sin^2\beta-\tfrac{1}{2}\sin 2\alpha\sin 2\beta\cos(d_{s1}-d_{p1})\}^{\frac{1}{2}}, \tag{9}$$

$$F=\cos\gamma\{\cos^2\alpha\sin^2\beta+\sin^2\alpha\cos^2\beta+\tfrac{1}{2}\sin 2\alpha\sin 2\beta\cos(d_{s1}-d_{p1})\}^{\frac{1}{2}}. \tag{10}$$

If the same plane polarized monochromatic light wave is simultaneously allowed to enter the lower half of the prism aperture and to emerge from the upper (see Fig. 3), a completely identical set of equations can be written for $\mathfrak{A}_{s3}$ and $\mathfrak{A}_{p3}$ with α, β, and γ replaced by δ, ϵ, and η. The exact forms of these equations are recorded in the earlier paper and will not be written here. The other quantities defined by Eqs. (3) to (10) also have an identical set for the $\mathfrak{A}_{s3}$ and $\mathfrak{A}_{p3}$ waves defined in terms of the azimuth angles δ, ϵ, η.

It is important to notice that the only difference between A_{s3} and A_{p3} (the same is also true for $\mathfrak{A}_{s3}$ and $\mathfrak{A}_{p3}$ components) for a two internal reflection roof prism with uncoated reflecting surfaces as compared with A_{s3}' and A_{p3}' for a three internal reflection roof prism with uncoated reflecting surfaces is the absence of d_{s3} and d_{p3} (phase changes after reflection at the third reflecting surface of a three internal reflection roof prism) in A_{s3} and A_{p3}.

These types of equations for the emergent waves for the two types of prisms are applicable only to prisms with uncoated reflecting surfaces for which all internal reflections are always beyond the critical angle. The preceding equations in no way apply to a roof prism in which reflection at any surface occurs below the critical angle or for a roof prism having any of the reflecting surfaces coated with a metal. For any given incident azimuth angle α, it will be possible from these equations to determine A_{s3}, A_{p3}, $\mathfrak{A}_{s3}$, and $\mathfrak{A}_{p3}$ in Fig. 3. Knowing both the amplitude and phase of each of these four waves, the ellipticity of the emergent light in the upper and lower halves of the prism aperture in Fig. 3 also can be evaluated.

3. FORMS OF DIFFRACTION PATTERNS FOR PRISMS WITH UNCOATED REFLECTING SURFACES

To be able to calculate the forms of the diffraction patterns for such roof prisms, it is now necessary to combine in the focal plane of the focusing lens the four waves represented at the right in Fig. 3 using the usual methods of Fraunhofer diffraction. These detailed calculations have been done in the earlier paper[1] and will not be repeated here. Briefly, the method for arriving at the expression for the intensity distribution in the diffraction pattern is the following. The two "s" components (A_{s3} and $\mathfrak{A}_{s3}$) designated in Fig. 3 at the right are each integrated over their respective regions of the aperture and then added taking into account their respective amplitudes and phases.[3] The two "p" components (A_{p3} and $\mathfrak{A}_{p3}$) are similarly integrated over their respective regions of the aperture and combined. The resultant intensity in the focal plane of the lens will then, since these two combined vibrations are perpendicular to each other, be proportional to the sum of the squares of the amplitudes of these two combined vibrations. The final equation arrived at in the earlier paper[1] for the intensity distribution in the diffraction pattern was||

[3] The procedure for combining these waves two at a time is shown theoretically and experimentally in A. I. Mahan J. Opt. Soc. Am. **37**, 852 (1947).

|| The R's and $\mathfrak{R}$'s in the same equation in the earlier paper were interchanged by mistake. This error does not in the earlier paper affect the form of the diffraction pattern in unpolarized light but does invert all the calculated patterns left and right for polarized light.

$$J=(4ab)^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}$$
$$\times\{A_0^2+\bar{A}_{s3}\bar{\alpha}_{s3}\cos[V-(R_{s3}-\Re_{s3})]$$
$$+\bar{A}_{p3}\bar{\alpha}_{p3}\cos[V-(R_{p3}-\Re_{p3})]\},\quad(11)$$

where U and V are given by

$$U=\frac{2\pi a\xi}{\lambda F},\quad V=\frac{2\pi b\mu}{\lambda F}\cdot\qquad(12)$$

U and V in these last two relations are expressed in radians. In Eq. (11) $\bar{A}_{s3}$, $\bar{A}_{p3}$, $\bar{\alpha}_{s3}$, $\bar{\alpha}_{p3}$ are the amplitudes of the waves (see Eqs. (1) and (2)) emerging from the upper and lower halves of the aperture, ξ and μ are the coordinates in the focal plane of the focusing lens of focal length F and λ is the wave-length. In Fig. 3, ξ is the coordinate in the focal plane of the lens parallel to the direction of A_{p3} while μ is the coordinate parallel to A_{s3}. From this figure also 2a and 2b can be seen to be the length and width of the emergent aperture of the prism.

It is important to notice that the equations for the diffraction pattern forms of a two and three internal reflection roof prism (of the special type considered) having uncoated reflecting roof surfaces are of exactly the same form while the equations for the four emergent plane waves for the two types of prisms are slightly different (see Eqs. (1) and (2) of the present paper as compared with Eqs. (9) and (10) of the earlier paper). The three reflection prism contains d_{s3} and d_{p3} in the phase factors while the two reflection prism does not. This identity in the form of the diffraction pattern equations for the two types of prisms arises from the fact that phase differences between corresponding waves in the two halves of the aperture (A_{s3} and α_{s3} in Fig. 3) always appear in the considerations leading up to Eq. (11) of the present paper so that since the d_{s3} and d_{p3} appear only in the phase factors of the four waves for the three reflection roof prism, they automatically disappear in the final equation for the diffraction pattern. Equation (11) can, therefore, be expected to apply to two and three internal reflection roof prisms (of the special type mentioned) having uncoated reflecting surfaces.

The remaining part of the theoretical discussion in this paper will be devoted primarily to the reducing of this equation to a simpler form so that the diffraction pattern forms for two and three internal reflection roof prisms can be calculated directly from a knowledge only of the *refractive index* of the prism, *the angular deviation at the roof edge*, and the *incident azimuth angle* of the plane polarized light if the prism is illuminated with plane polarized light. Such a simplification of this equation makes it no longer necessary to undertake a detailed study of the geometry of each prism and to evaluate β, γ, δ, ϵ, and η as was done in the earlier paper.

The first step in reducing this equation to a more simplified form is that of expanding the cosine terms in Eq. (11) and then to group the coefficients of $\cos V$ and $\sin V$. If this is done the following equation results.

$$J=(4ab)^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}\{A_0^2+[\bar{A}_{s3}\bar{\alpha}_{s3}\cos R_{s3}\cos\Re_{s3}+\bar{A}_{s3}\bar{\alpha}_{s3}\sin R_{s3}\sin\Re_{s3}$$
$$+\bar{A}_{p3}\bar{\alpha}_{p3}\cos R_{p3}\cos\Re_{p3}+\bar{A}_{p3}\bar{\alpha}_{p3}\sin R_{p3}\sin\Re_{p3}]\cos V+[\bar{A}_{s3}\bar{\alpha}_{s3}\sin R_{s3}\cos\Re_{s3}-\bar{A}_{s3}\bar{\alpha}_{s3}\cos R_{s3}\sin\Re_{s3}$$
$$+\bar{A}_{p3}\bar{\alpha}_{p3}\sin R_{p3}\cos\Re_{p3}-\bar{A}_{p3}\bar{\alpha}_{p3}\cos R_{p3}\sin\Re_{p3}]\sin V\}.\quad(13)$$

It will be a little more convenient in the following development to write this equation in the following simpler form

$$J=(4ab)^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}\{A_0^2+G\cos V+K\sin V\},\quad(14)$$

where as suggested by the previous equation, G and K are simply the coefficients of the $\cos V$ and $\sin V$ terms. From equations of the form of (5) and (6), it is possible to substitute for the various trigonometric functions involving R_{s3}, R_{p3}, $\Re_{s3}$ and $\Re_{p3}$. In making these substitutions, the denominators of the expressions corresponding to these sine and cosine terms will each be found to be an amplitude of one of the four emergent waves in the aperture of the prism (see Eqs. (1) and (2)). If substitutions for each of these trigonometric functions are made, the following values of G and K will be found.

$$G=A_0^2\{[C\cos(R_{s2}+d_{s2})-D\cos(R_{p2}+d_{p2})][\mathfrak{C}\cos(\mathfrak{R}_{s2}+d_{s2})-\mathfrak{D}\cos(\mathfrak{R}_{p2}+d_{p2})]$$
$$+[C\sin(R_{s2}+d_{s2})-D\sin(R_{p2}+d_{p2})][\mathfrak{C}\sin(\mathfrak{R}_{s2}+d_{s2})-\mathfrak{D}\sin(\mathfrak{R}_{p2}+d_{p2})]$$
$$+[E\cos(R_{s2}+d_{s2})+F\cos(R_{p2}+d_{p2})][\mathfrak{E}\cos(\mathfrak{R}_{s2}+d_{s2})+\mathfrak{F}\cos(\mathfrak{R}_{p2}+d_{p2})]$$
$$+[E\sin(R_{s2}+d_{s2})+F\sin(R_{p2}+d_{p2})][\mathfrak{E}\sin(\mathfrak{R}_{s2}+d_{s2})+\mathfrak{F}\sin(\mathfrak{R}_{p2}+d_{p2})]\},\quad(15)$$

$$K=A_0^2\{[C\sin(R_{s2}+d_{s2})-D\sin(R_{p2}+d_{p2})][\mathfrak{C}\cos(\mathfrak{R}_{s2}+d_{s2})-\mathfrak{D}\cos(\mathfrak{R}_{p2}+d_{p2})]$$
$$-[C\cos(R_{s2}+d_{s2})-D\cos(R_{p2}+d_{p2})][\mathfrak{C}\sin(\mathfrak{R}_{s2}+d_{s2})-\mathfrak{D}\sin(\mathfrak{R}_{p2}+d_{p2})]$$
$$+[E\sin(R_{s2}+d_{s2})+F\sin(R_{p2}+d_{p2})][\mathfrak{E}\cos(\mathfrak{R}_{s2}+d_{s2})+\mathfrak{F}\cos(\mathfrak{R}_{p2}+d_{p2})]$$
$$-[E\cos(R_{s2}+d_{s2})+F\cos(R_{p2}+d_{p2})][\mathfrak{E}\sin(\mathfrak{R}_{s2}+d_{s2})+\mathfrak{F}\sin(\mathfrak{R}_{p2}+d_{p2})]\}.\quad(16)$$

Taking advantage now of the equations of the form of (3) and (4) for R_{s2} and R_{p2} and a similar set for $\mathfrak{R}_{s2}$ and $\mathfrak{R}_{p2}$ which can be obtained by replacing α, β, and γ by δ, ϵ, and η, the sine and cosine terms involving these quantities can also be substituted for in the previous expressions for G and K. If Eqs. (15) and (16) are first expanded and these substitutions made and the various terms collected, the values of G and K found are

$$G=A_0^2\{\cos(\alpha-\delta)\cos(\beta-\epsilon)\cos(\gamma-\eta)-\sin(\alpha-\delta)\sin(\beta-\epsilon)\cos(\gamma-\eta)\cos(d_{s1}-d_{p1})$$
$$-\cos(\alpha-\delta)\sin(\beta-\epsilon)\sin(\gamma-\eta)\cos(d_{s2}-d_{p2})-\sin(\alpha-\delta)\cos(\beta-\epsilon)\sin(\gamma-\eta)$$
$$\cdot\cos(d_{s1}-d_{p1})\cos(d_{s2}-d_{p2})+\sin(\alpha-\delta)\cos(\beta+\epsilon)\sin(\gamma-\eta)\sin(d_{s1}-d_{p1})\sin(d_{s2}-d_{p2})\},\quad(17)$$

$$K=A_0^2\{\sin(\alpha+\delta)\sin(\beta-\epsilon)\cos(\gamma-\eta)\sin(d_{s1}-d_{p1})+\sin(\alpha+\delta)\cos(\beta-\epsilon)\sin(\gamma-\eta)$$
$$\cdot\sin(d_{s1}-d_{p1})\cos(d_{s2}-d_{p2})+\cos(\alpha+\delta)\sin(\beta+\epsilon)\sin(\gamma-\eta)\sin(d_{s2}-d_{p2})$$
$$+\sin(\alpha+\delta)\cos(\beta+\epsilon)\sin(\gamma-\eta)\cos(d_{s1}-d_{p1})\sin(d_{s2}-d_{p2})\}.\quad(18)$$

To simplify these equations further, it now becomes necessary to take advantage of the general symmetry properties of roof prisms. Such symmetry properties are not obvious but can readily be established either trigonometrically or by studying an actual model of the prism as was done in the earlier paper. In this model, the rays in the prism were represented by strings and matches were mounted on these strings to represent the perpendicular and parallel components of the electric vector at each roof surface and in the emergent aperture of the prism (see Fig. 1). If now one follows the paths of the two sets of rays incident on the upper and lower halves of the prism aperture of such a model, one notices that along one path the positive directions of the "s" vibrations rotate clockwise while those along the other path rotate counterclockwise by the same amount. The first symmetry relations which can be made use of are then:

$$\epsilon=-\beta,\quad\eta=-\gamma.\quad(19)$$

Further there is always a constant difference H between the entering azimuth angles for the two halves of the prism so that

$$\delta-\alpha=H.\quad(20)$$

The angle of incidence on each of the roof surfaces for rays traveling parallel to the ray of Fig. 2 along the two different paths through the prism will also be found to always be the same for all accurately made roof prisms. Since the phase changes upon reflection at any glass-air surface beyond the critical angle are only functions of the angle of incidence and refractive index as given by Fresnel's equation (see Eq. (26)), it follows that the phase changes upon reflection for the two roof surface reflections will be the same so that the following simplifications can also be introduced.

$$d_{s1}-d_{p1}=d_{s2}-d_{p2}=\Phi.\quad(21)$$

If now the symmetry relations in Eqs. (19) to (21) are made use of in simplifying G and K given in Eqs. (17) and (18), we find that

$$G=A_0^2\{\sin H[\sin2\beta\cos2\gamma\cos\Phi$$
$$+\cos2\beta\sin2\gamma\cos^2\Phi-\sin2\gamma\sin^2\Phi$$
$$+\cos H[\cos2\beta\cos2\gamma-\sin2\beta\sin2\gamma\cos\Phi]\},\quad(22)$$

$$K=A_0^2\{\sin(2\alpha+H)\sin\Phi[\sin2\beta\cos2\gamma$$
$$+\cos2\beta\sin2\gamma\cos\Phi+\sin2\gamma\cos\Phi]\}.\quad(23)$$

These equations although simpler than the earlier form still make it necessary to know quite a bit about the geometry of each roof prism before its diffraction pattern form can be calculated. To make these calculations still simpler, it is necessary now to know still more about the general geometry of roof prisms, their rays and the directions of vibration of their "s" and "p" components at each reflecting roof surface. To develop these simplified equations, a generalized type

of two reflection¶ roof prism as shown in Fig. 4 was visualized. Angle d is the angle in the plane of the figure between the incident ray and the normal to the roof edge, while D is the angular deviation of the incident ray at the roof edge. If one considers only the rays which are incident normally on the entering face of the prism, D can also as seen from the figure be associated directly with the angular deviation produced by the prism. However, when other rays parallel to the plane of Fig. 4 are allowed to be incident on a given prism and Snell's Law of refraction applied at the entering and leaving faces of the prism, the angular deviation D at the roof edge will have a different value from the angular deviation produced by the complete prism. Rigorously speaking then, D for the more general case must in the following equations be associated directly with the deviation at the roof edge for the particular roof prism. All the equations which follow can be developed in terms of either d or D but the latter was chosen because it is the constant most usually associated with prisms.

It is now possible to develop a table of direction cosines describing the detailed geometry of these generalized types of roof prisms in terms of angle D. The methods for doing this will not be discussed in detail for they have already been described in conjunction with Fig. 6 of the earlier paper. Briefly, the methods involved can be stated in conjunction with Fig. 1 of the present paper. If one looks carefully at the "s" vibrations in this diagram, they will be seen to rotate clockwise as one proceeds along the ray path through the prism. The angles β and γ by convention are then positive. At each point of incidence on a roof surface, the direction cosines of the incident ray, reflected ray, and the "s" and "p" vibrations are evaluated in terms of D in the manner suggested in the earlier paper. The correct signs were always checked by either looking at Fig. 1 or a prism model. The direction cosine tables thus obtained are included in Tables I and II.

Having now this table*** of direction cosines for an arbitrary roof prism at our disposal, we can check not only the symmetry relations suggested in Eqs. (19) but we can also find out new facts about these prisms. If one makes use of the cosine law for finding the angle between two lines whose direction cosines are known, one can find values for the sine and cosine of the angles β, γ and H (the latter angle can be looked upon as the angle between s_1 and s_1' given in the tables). These calculations are rather simple and when written down

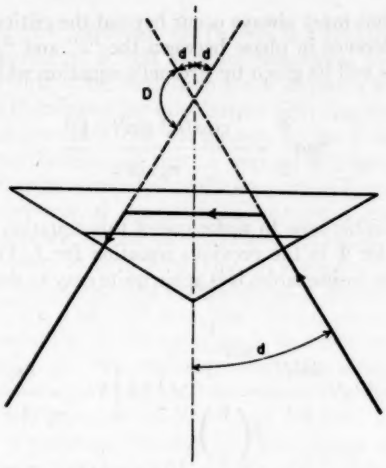


FIG. 4. Ray diagram for a generalized roof prism.

will be found to give the following values:

$$\sin\beta=\frac{2\cos\tfrac{1}{2}D}{\cos^2\tfrac{1}{2}D+1},\quad \cos\beta=\frac{\sin^2\tfrac{1}{2}D}{\cos^2\tfrac{1}{2}D+1},$$
$$\gamma=90°+\beta/2,\qquad H=180°-\beta. \tag{24}$$

Substituting these values for γ and H in Eqs. (22) and (23) for G and K and then substituting for β in the resulting expansions, we find that J in the equation utilizing these resulting values of G and K reduces to the following general equation for the diffraction pattern form.

$$J=(4ab)^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\dfrac{V}{2}}{2\left(\dfrac{V}{2}\right)^2}A_0^2$$
$$\times\left\{1+\left[1-\frac{32\cos^2\tfrac{1}{2}D\sin^4\tfrac{1}{2}D}{(\cos^2\tfrac{1}{2}D+1)^4}\cos^4\frac{\Phi}{2}\right]\cos V\right.$$
$$+\frac{8\sin^4\tfrac{1}{2}D\cos\tfrac{1}{2}D\sin\Phi\cos^2\dfrac{\Phi}{2}}{(\cos^2\tfrac{1}{2}D+1)^4}$$
$$\left.\times[\sin2\alpha\sin^2\tfrac{1}{2}D-2\cos2\alpha\cos\tfrac{1}{2}D]\sin V\right\}. \tag{25}$$

In doing calculations for the diffraction pattern form from Eq. (25), one still must evaluate Φ before any numerical calculations can be made. The only other possible simplification then is that of substituting for Φ in terms of D and the refractive index n_g. Since for the roof prisms with which this theory is concerned,

¶ As was suggested earlier, the theory as it is developed in this paper will also apply to a generalized three reflection roof prism of a type which could also be indicated in this figure by adding a third reflecting glass-air surface perpendicular to the plane of the drawing for the emergent prism ray, such that reflection occurs beyond the critical angle.

*** These tables have been checked numerically both for the 90° deviation Amici roof prism and the odd-shaped three reflection roof prism described in the earlier paper.

reflections must always occur beyond the critical angle, the difference in phase between the "s" and "p" components will be given by Fresnel's equation which is[4]

$$\tan\frac{\Phi}{2}=-\frac{\cos i(n_g^2\sin^2 i-1)^{\frac{1}{2}}}{n_g\sin^2 i}. \tag{26}$$

It is possible now to make use of this equation to substitute for Φ in the previous equation for J. From the direction cosine tables it is again quite easy to determine i for a roof prism of angular deviation D at the roof edge from the formula

$$\sin i=\frac{(3+\cos D)^{\frac{1}{2}}}{2}. \tag{27}$$

If these last two equations are used to eliminate Φ from Eq. (25) for J, one obtains a final equation for the diffraction pattern of a generalized roof prism with uncoated reflecting roof surfaces which has the form given by

$$J=(4ab)^2A_0^2\cdot\frac{\sin^2 U}{U^2}\cdot\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}\times\left\{1+\left[1-\frac{8n_g^4\sin^4\frac{1}{2}D\cos^2\frac{1}{2}D}{[n_g^2(1+\cos^2\frac{1}{2}D)-\sin^2\frac{1}{2}D]^2}\right]\cos V\right.$$
$$\left.-\frac{4n_g^3\sin^5\frac{1}{2}D\cos\frac{1}{2}D[n_g^2(1+\cos^2\frac{1}{2}D)-2]^{\frac{1}{2}}}{[n_g^2(1+\cos^2\frac{1}{2}D)-\sin^2\frac{1}{2}D]^2(1+\cos^2\frac{1}{2}D)}[\sin 2\alpha\sin^2\tfrac{1}{2}D-2\cos 2\alpha\cos\tfrac{1}{2}D]\sin V\right\}. \tag{28}$$

Knowing that the S_1 vibration forms an angle θ with the plane of Fig. 4 in the plane of the entrance aperture given by

$$\cos\theta=\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}. \tag{29}$$

(Can be checked from Table I), it is quite easy to fix the azimuth angle in the plane of the entrance aperture of the prism and, hence, to evaluate the diffraction pattern form for polarized light of any azimuth angle α incident on a prism with uncoated reflecting roof surfaces. It is now necessary to know only n_g, D and α to complete these calculations.

In normal usage, one is not very much interested in

TABLE I. Direction cosines of incident rays, reflected rays, "s" and "p" vibrations and equations of planes of incidence for rays entering upper half of prism aperture and emerging from lower.

Equation of first plane of incidence $(\cos\frac{1}{2}D)x+(\cos\frac{1}{2}D)y+(\sin\frac{1}{2}D)z=0$			
Incident ray	$+\sin\frac{1}{2}D$	0	$-\cos\frac{1}{2}D$
Surface normal	$+\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$	0
Reflected ray	0	$-\sin\frac{1}{2}D$	$+\cos\frac{1}{2}D$
S_1	$+\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\sin\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_1 before reflection	$+\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_1 after reflection	$+\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
Equation of second plane of incidence $(\cos\frac{1}{2}D)x-(\cos\frac{1}{2}D)y-(\sin\frac{1}{2}D)z=0$			
Incident ray	0	$+\sin\frac{1}{2}D$	$-\cos\frac{1}{2}D$
Surface normal	$+\frac{1}{\sqrt{2}}$	$+\frac{1}{\sqrt{2}}$	0
Reflected ray	$+\sin\frac{1}{2}D$	0	$+\cos\frac{1}{2}D$
S_2	$-\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\sin\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_2 before reflection	$+\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_2 after reflection	$+\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
Vertical S_2 vibration	0	-1	0
Horizontal P_2 vibration	$-\cos\frac{1}{2}D$	0	$+\sin\frac{1}{2}D$

[4] M. Born, *Optik* (Verlagsbuchhandlung, Julius Springer, Berlin, 1933), p. 43.

the diffraction pattern form in polarized light but is more interested in how the prism behaves in unpolarized light. To arrive at a mathematical expression for the diffraction pattern in unpolarized light, the intensity J in Eq. (28) must be integrated and averaged for values of α between 0° and 180°. If all values of α are equally probable, this means that an integral of the form $(1/\pi)\int_0^\pi J d\alpha$ must be evaluated. If this integration is done, terms of the form $\int_0^\pi \sin 2\alpha d\alpha$ and $\int_0^\pi \cos 2\alpha d\alpha$ will be found to vanish so that in unpolarized light the intensity distribution will be of the following simpler form

$$J=(4ab)^2A_0^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}$$

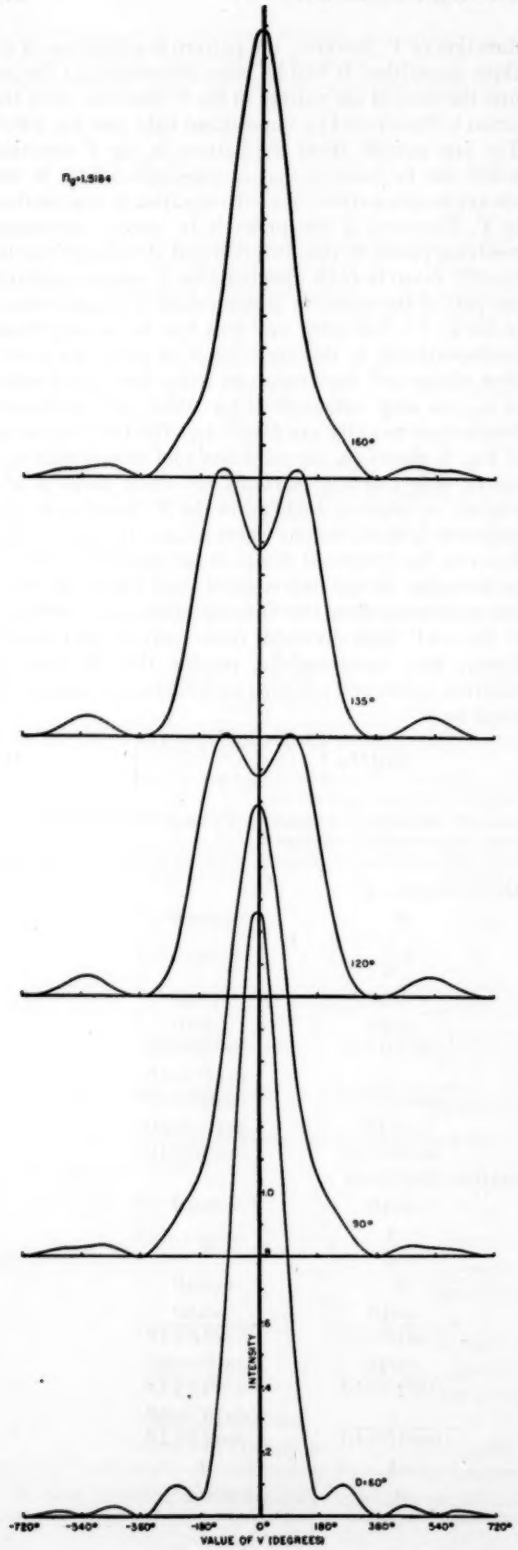
$$\times\left\{1+\left[1-\frac{8n_g^4\sin^4\frac{1}{2}D\cos^2\frac{1}{2}D}{[n_g^2(1+\cos^2\frac{1}{2}D)-\sin^2\frac{1}{2}D]^2}\right]\cos V\right\}. \quad (30)$$

Having derived Eqs. (28) and (30) for the diffraction pattern form in polarized and unpolarized light, a few remarks can now be made about its form for different values of D, n_g and α. From both of these equations, the first remark that can be made is that the diffraction pattern in a direction parallel to the roof edge will for both polarized and unpolarized light always be of the usual Fraunhofer form $\sin^2U/U^2$ for all values of D, n_g and α since it is independent of these quantities. In the direction of V, however, the pattern is a function of all three quantities. It will be more convenient to discuss first the form of the pattern in the V direction when the prism is illuminated by unpolarized light (see Eq. (30)). The first remark about the pattern in the V direction which can be made is that in unpolarized light it will always be symmetrical since the equation is symmetrical in V. However, if the prism is to have a maximum resolving power in this direction and the image is to be equally sharp in both directions for a square aperture, the part of the equation dependent on V should reduce to $\sin^2V/V^2$. The only way this can be accomplished mathematically in this equation is to make the coefficient of the $\cos V$ term reduce to unity. For a fixed value of n_g, the only values of D for which this coefficient does reduce to unity are $D=0°$ and $D=180°$. In terms of Fig. 4, therefore, the only two roof prisms with uncoated reflecting roof surfaces for which there is absolutely no angular doubling in the V direction in unpolarized light will be one which returns the light in the direction from which it comes or one for which there is no deviation at the roof edge. *As* one allows D to increase between these two limiting values, the coefficient of the $\cos V$ term decreases from unity at first rather slowly, then more rapidly, passing through zero to negative values and reaching a minimum at a value of D given by

$$\sin\tfrac{1}{2}D=\left\{\frac{3n_g^2-n_g(5n_g^2-4)^{\frac{1}{2}}}{n_g^2+1}\right\}^{\frac{1}{2}}. \quad (31)$$

TABLE II. Direction cosines of incident rays, reflected rays, "*s*" and "*p*" vibrations and equations of planes of incidence for rays entering lower half of prism aperture and emerging from upper.

Equation of first plane of incidence $(\cos\frac{1}{2}D)x-(\cos\frac{1}{2}D)y+(\sin\frac{1}{2}D)z=0$			
Incident ray	$+\sin\frac{1}{2}D$	0	$-\cos\frac{1}{2}D$
Surface normal	$+\frac{1}{\sqrt{2}}$	$+\frac{1}{\sqrt{2}}$	0
Reflected ray	0	$+\sin\frac{1}{2}D$	$+\cos\frac{1}{2}D$
S_1'	$-\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\sin\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_1' before reflection	$+\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_1' after reflection	$+\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
Equation of second plane of incidence $(\cos\frac{1}{2}D)x+(\cos\frac{1}{2}D)y-(\sin\frac{1}{2}D)z=0$			
Incident ray	0	$-\sin\frac{1}{2}D$	$-\cos\frac{1}{2}D$
Surface normal	$+\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$	0
Reflected ray	$+\sin\frac{1}{2}D$	0	$+\cos\frac{1}{2}D$
S_2'	$+\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\sin\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_2' before reflection	$+\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$+\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
P_2' after reflection	$+\frac{\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{1}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$	$-\frac{\sin\frac{1}{2}D\cos\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^{\frac{1}{2}}}$
Vertical S_2' vibration	0	-1	0
Horizontal P_2' vibration	$-\cos\frac{1}{2}D$	0	$+\sin\frac{1}{2}D$



Beyond this minimum, the coefficient of the cos$V$ term begins to increase with further increases in D and rises sharply going through zero and again reaching unity at $D=180°$. In terms of the doubling of the diffraction pattern in a direction perpendicular to the roof edge, the doubling for a glass of refractive index n_0 reaches a maximum at a value of D given by Eq. (31).

The term doubling of the diffraction pattern may be a little misleading particularly for small values of D and values of D very near to 180°. To show just how this doubling in unpolarized light appears as D is changed, several of these diffraction patterns in a direction perpendicular to the roof edge were calculated from Eq. (30) for roof prisms having a refractive index of 1.5184†† when they are illuminated with green mercury light. The forms of these patterns with ordinates multiplied by two are shown in Fig. 5 for the values of D used. As suggested earlier, for values of $D=0°$ and $D=180°$ the pattern is of the conventional Fraunhofer form. To avoid additional complications in the figure, these curves have been left out. Their forms, however, can be seen in Fig. 9. As one proceeds away from $D=0°$, the pattern changes in form at first very slowly. The changes which take place consist of a lowering and broadening of the central band and a gradual disappearance of every other minimum in the outer band structure. Up to values of $D=60°$, these changes are not too pronounced for all the secondary bands can still be seen in this pattern in Fig. 5. For $D=90°$, every other band in the outer band structure has practically disappeared and the central band is now materially broader. For $D=120°$ and $D=135°$, the central band splits into two bands with a minimum at the center of the band system. For a roof prism of this particular refractive index, the doubling according to Eq. (31) reaches a maximum near a value of $D=132°$ so that the largest possible doubling is very nearly that shown in Fig. 5 for $D=135°$. For still larger values of D, the diffraction pattern form rapidly goes over again into the conventional Fraunhofer pattern. At $D=160°$ the doubling in the central band has already disappeared and the outer bands are just beginning to split into two separate bands of the Fraunhofer shape. The term doubling in this paper refers to either a broadening or splitting of the central diffraction maximum of the form shown in Fig. 5.

The form of the diffraction pattern in a direction perpendicular to the roof edge in polarized light described by Eq. (28) is a little more complicated to discuss. First of all the pattern will, in general, be unsym-

†† The authors are indebted to Herman Templin of the Physical Optics Division who calculated the constants for Hartman's dispersion formula for borosilicate crown making it possible to evaluate n_0 for the green mercury line.

FIG. 5. Forms of diffraction patterns in unpolarized light in a direction perpendicular to the roof edge for roof prisms with uncoated roof surfaces having different angular deviations D at the roof edge.

metrical for all values of D between 0° and 180° since Eq. (28) is unsymmetrical in V. For a prism of fixed D, the diffraction pattern will be periodic in α its form being repeated for every 180° change in α. In this period in α between 0° and 180°, there will be two values of α for which the $\sin V$ term will vanish. These values of α will be given by

$$\tan\alpha = -\frac{\sin^2\tfrac{1}{2}D}{2\cos\tfrac{1}{2}D} \pm \left(\frac{\sin^4\tfrac{1}{2}D}{4\cos^2\tfrac{1}{2}D}+1\right)^{\frac{1}{2}}. \qquad (32)$$

For these two incident azimuth angles, the diffraction pattern again becomes symmetrical and of identically the same form as when the prism is illuminated with unpolarized light (see Eq. (30)). For other values of α between 0° and 180°, the contribution of the $\sin V$ term is added on one side of the diffraction pattern and subtracted on the other due to its non-symmetry in V. For each roof prism of angular deviation D, the diffraction pattern form, therefore, oscillates back and forth about the symmetric pattern for unpolarized light with a period of 180° in α. The magnitude of these changes in the diffraction pattern form with α are functions of D and n_g. For angles of $D=0°$ and $D=180°$, the contribution of the $\sin V$ term vanishes. These prisms, therefore, always have a symmetrical diffraction pattern of the Fraunhofer form $\sin^2 V/V^2$ in a direction perpendicular to the roof edge which is independent of the entering azimuth angle α of the plane polarized light and the refractive index n_g. If now for a fixed n_g and entering azimuth angle α the angular deviation at the roof edge D is increased, the contribution to the asymmetry of the diffraction pattern due to the $\sin V$ term starts at zero for $D=0°$ increases at first slowly with D then more rapidly finally reaches a maximum and then recedes rapidly to zero at $D=180°$. In general, one can say that the larger the deviation of the pattern from the Fraunhofer pattern in unpolarized light, the larger will be the asymmetry in the patterns when the prism is illuminated with polarized light of different entering azimuth angles. Similar studies of the form of the diffraction pattern in a direction perpendicular to the roof edge for fixed D and changing refractive index n_g show for incident unpolarized light that the angular doubling decreases very slightly with increasing n_g.

4. FORMS OF DIFFRACTION PATTERNS FOR PRISMS WITH COATED REFLECTING SURFACES

All of the discussion previously has been concerned with roof prisms in which the two or three internal reflections take place beyond the critical angle. It is now quite interesting to ask what will happen to the diffraction pattern form if the boundary conditions at the reflecting surfaces are changed, for example, by depositing an opaque layer of silver over these surfaces. To develop exact equations for this more general case of a prism with arbitrary boundary conditions at the internal reflecting surfaces, it is necessary to start

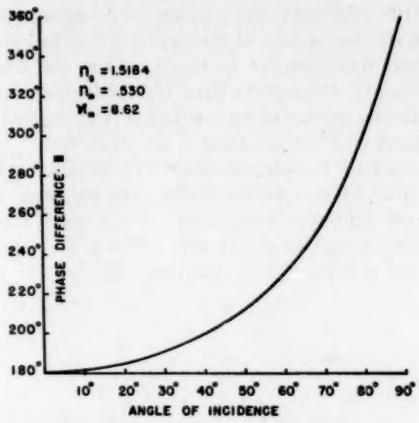


FIG. 6. Difference in phase between the perpendicular and parallel components of the electric vector for different angles of incidence on a glass-silver reflecting surface.

again at the beginning of the theory assuming an initial plane polarized wave is entering the prism. This wave must be resolved again about the directions of the "s" and "p" components at the first roof surface taking into account now not only the phase changes after reflection but also the fraction of each component reflected. These reflected components must be resolved about the second roof surface and so on until one again arrives at a more complex set of equations similar to (1) to (10). These equations then have to be substituted in Eq. (11). If the prism under consideration is a three internal reflection roof prism, the first assumption which has to be made before any of the terms can be combined is that the fraction of the "s" and "p" components reflected at the third coated surface are equal ($\rho_{s3}=\rho_{p3}=1$). The only angles of incidence on such an air-silver interface where this equality can be realized are at 0° or 90° (see Fig. 7) and for these values it will be found impossible or impracticable to make a three reflection roof prism. Since this equality cannot be obtained at other angles of incidence for a glass-metal boundary, both ρ_{s3} and ρ_{p3} throughout this paper have been assumed to be unity which means that the third reflecting surface of each three internal reflection roof prism must be uncoated and reflection at this surface must take place beyond the critical angle. Clearly, therefore, the following equation for the diffraction pattern first of all will not, for example, apply to a penta prism with a roof over one surface whose three reflecting surfaces are coated with silver. The second assumption which has to be made to simplify the equations both for the two and three internal reflection roof prisms is that the fraction of the "s" and "p" components reflected at the first roof surface are the same as those at the second. This restricts the direction of the incident rays to rays which are parallel to the plane of Fig. 2 as was done in arriving at Eqs. (28) and (30) for the uncoated prism. If after making these assumptions,

Eqs. (19), (20), (21), and (24) are taken advantage of to reduce the complexity of the equations, an equation for polarized light similar to Eq. (25) for the uncoated prism can be developed with arbitrary boundary conditions at the reflecting roof surfaces. Although we have developed such an equation it becomes rather long to write down for the case of incident plane polarized light. In normal usage, prisms of this sort are used in unpolarized light so the equation for this particular case only will be written down. For a two or three internal reflection roof prism this equation is‡‡

$$J=(4ab)^2A_0^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}\times\left\{1+\frac{4\sin^4\frac{1}{2}D\cos^2\frac{1}{2}D}{(\cos^2\frac{1}{2}D+1)^4}\left[\frac{\sin^4\frac{1}{2}D}{8\cos^2\frac{1}{2}D}(\rho_s^4+\rho_p^4)-2\cos\Phi(\rho_s^3\rho_p+\rho_s\rho_p^3)-\rho_s^2\rho_p^2\times\left(2\cos^2\Phi-\frac{4\cos^2\frac{1}{2}D}{\sin^4\frac{1}{2}D}\right)\right]\cos V\right\}. \quad (33)$$

In this equation ρ_s and ρ_p are the fractions of the perpendicular and parallel components of the electric vector reflected at the glass-silver roof surface boundary and Φ again is the difference in phase between these two components after reflection at the same boundary.

Equation (33) for the form of the diffraction pattern is written for arbitrary boundary conditions at the reflecting roof surfaces. In principle it can be applied to thin films over these roof surfaces but in order to avoid the complications of interference and absorption effects within these layers, the deposited layers will be assumed to be thick enough so that multiple reflections within the film will not arise. Before these diffraction pattern forms can be calculated it is necessary to evaluate Φ, ρ_s, and ρ_p at a glass-silver interface. This is a problem in electromagnetic light theory which has been discussed by W. König in his classical article on Electromagnetic Light Theory.[5] The only modification in König's final equations which has to be made to fit the glass-metal interface is that of replacing n_0 by n_m/n_g, n_m being the refractive index of the metal at normal incidence and n_g the refractive index for the glass. When these changes are made in König's final equations, the values of Φ, ρ_s, and ρ_p are

$$\tan\Phi=-\frac{2n_gB\sin i\tan i}{n_g^2\sin^2i\tan^2i-(A^2+B^2)}, \quad (34)$$

$$\rho_s^2=\frac{A^2+B^2-2n_gA\cos i+n_g^2\cos^2i}{A^2+B^2+2n_gA\cos i+n_g^2\cos^2i}, \quad (35)$$

$$\rho_p^2=\rho_s^2\frac{A^2+B^2-2n_gA\sin i\tan i+n_g^2\sin^2i\tan^2i}{A^2+B^2+2n_gA\sin i\tan i+n_g^2\sin^2i\tan^2i}. \quad (36)$$

In these equations the quantities A and B are defined by

$$A^2=\tfrac{1}{2}\{([n_m^2(1-\chi_m^2)-n_g^2\sin^2i]^2+4n_m^4\chi_m^2)^{\frac{1}{2}}+n_m^2(1-\chi_m^2)-n_g^2\sin^2i\}, \quad (37)$$

$$B^2=\tfrac{1}{2}\{([n_m^2(1-\chi_m^2)-n_g^2\sin^2i]^2+4n_m^4\chi_m^2)^{\frac{1}{2}}-n_m^2(1-\chi_m^2)+n_g^2\sin^2i\}. \quad (38)$$

χ_m in these equations is the absorption index for the opaque metal film covering the reflecting surfaces. Assuming now that the films used for covering these prisms fulfill the boundary conditions used in deriving these equations, it is possible for known values of n_g, n_m and χ_m at the glass-metal boundary to determine the form of the diffraction pattern for roof prisms with coated roof surfaces from Eq. (33). The form of the pattern in a direction parallel to the roof edge is still of the Fraunhofer form. Perpendicular to the roof edge, however, the diffraction pattern form is a function of D, n_g, n_m, and χ_m. Due to the complex way in which each of these variables appears in Eq. (33), it is not very easy to make any simple deductions about the dependence of the diffraction pattern form on the choice of these possible variables. It is rather easy, however, to evaluate Eq. (33) for the two limiting values of $D=0°$ and $D=180°$. If these two values of D are substituted in the equation, the V dependent parts of this equation

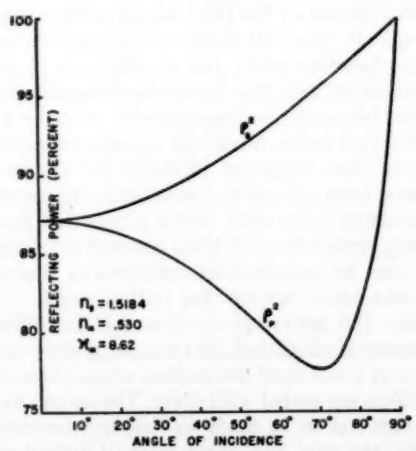


FIG. 7. Fractions of the incident intensity reflected at a glass-silver reflecting surface for different angles of incidence for directions of polarization of the electric vector parallel and perpendicular to the plane of incidence.

‡‡ As one check on the correctness of this equation, if one sets $\rho_s=\rho_p=1$, it should reduce to Eq. (25) with the $\sin V$ term absent and such will be found to be the case.

[5] W. König, *Handbuch der Physik*, Vol. 20 (Julius Springer Berlin, 1928), pp. 202–207; 240–243.

for these two values become

$$\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}[1+\rho_s^2\rho_p^2\cos V], \qquad (D=0°)$$

$$\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}\left[1+\frac{\rho_s^4+\rho_p^4}{2}\cos V\right]. \qquad (D=180°)$$

For $D=0°$ and $D=180°$ we see further from Eq. (27) that the angles of incidence on the roof surfaces for these two prisms are $i=90°$ and $i=45°$. Since for an angle of incidence of 90° ρ_s^2 and ρ_p^2 from Eqs. (35) and (36) are unity (see Fig. 7), the diffraction pattern in a direction perpendicular to the roof edge for a roof prism with $D=0°$ reduces to the Fraunhofer form. In the V direction for different values of D between these limits, the pattern for prisms with coated roof surfaces changes between the limiting forms given by

$$\frac{\sin^2 V}{V^2}, \qquad (D=0°,\ i=90°)$$

$$\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}\left[1+\frac{\rho_s^4+\rho_p^4}{2}\cos V\right]. \qquad (D=180°,\ i=45°) \qquad (39)$$

The simplest way to show how the diffraction pattern changes in the V direction as D is changed between these two limiting values was to calculate their forms for different D's. For the optical constants of silver, values were used which were given by Tate.[6] These values were obtained experimentally on a chemically deposited silver film on glass and were measured from the glass-silver surface. These are the values in which we shall be interested for substitutions in our equations since silver reflecting films normally used on such prisms are of the chemically deposited type and reflection takes place at the glass-silver boundary. The values for n_m and χ_m as obtained from this paper for the green mercury line were 0.530 and 8.62. These values by the author's own statement are not very accurate but since they were the only values which were found in the literature for a chemically deposited film as measured from the glass-metal surface, they were used in the following calculations. n_0 was assumed to have a value of 1.5184 which is the refractive index for borosilicate crown glass for the green mercury line. Using these values of n_0, n_m, and χ_m, it is now possible to evaluate Φ, ρ_s^2, and ρ_p^2 for different values of the angle of incidence i on the roof surfaces by substituting in Eqs. (34), (35), and (36). Figure 6 shows the dependence of the phase difference Φ on the angle of incidence i while Fig. 7 shows the values of ρ_s^2 and ρ_p^2 for different values of i. Knowing now Φ, ρ_s^2 and ρ_p^2 for all angles of incidence, we can now calculate the forms of the diffraction patterns for different roof prisms with silver coated roof surfaces by substituting various values of D directly in Eq. (33) after using Eq. (27) to determine

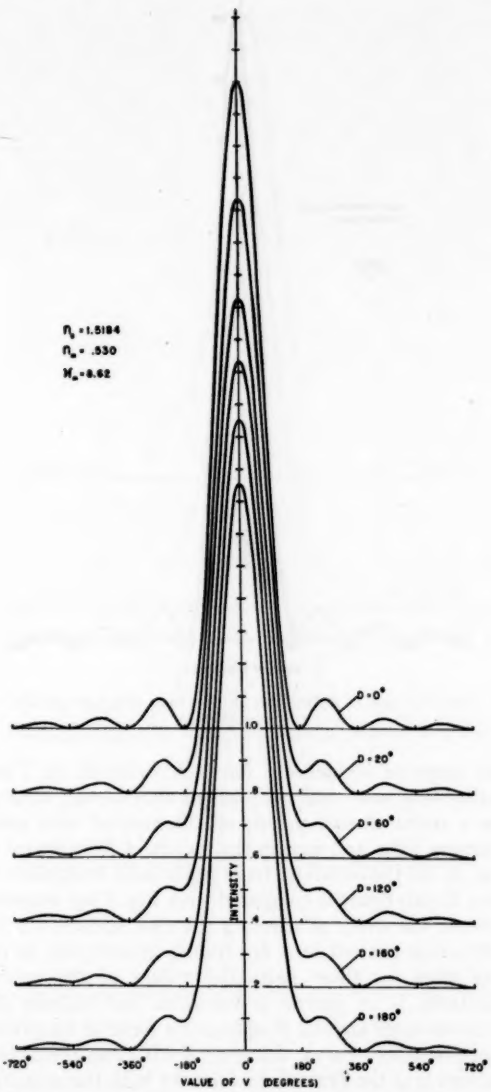


FIG. 8. Form of diffraction patterns in unpolarized light in a direction perpendicular to the roof edge for roof prisms with silver-coated roof surfaces having different angular deviations D at the roof edge.

[6] J. T. Tate, Phys. Rev. 34, 327 (1912).

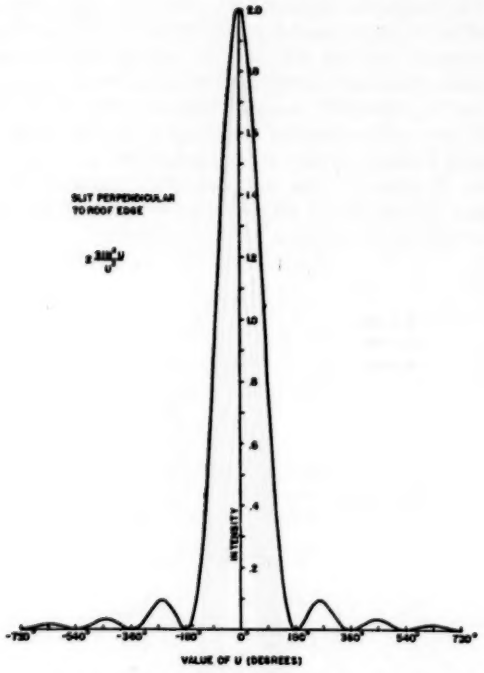


FIG. 9. Form of diffraction pattern in a direction parallel to the roof edge.

the angle of incidence i for each value of D. These rather long numerical calculations were carried through for a series of roof prisms all illuminated with green mercury light and having the values of D indicated in Fig. 8. All the ordinates have again been multiplied by two. If this figure is compared with Fig. 5 for uncoated prisms, the effect of silvering the roof surfaces on the diffraction pattern in a direction perpendicular to the roof edge for these particular values of the optical constants is in general a favorable one making the previous large angular doublings for some of the prisms much smaller. For a value of $D=0°$, the diffraction pattern is of the Fraunhofer form for both the uncoated and silver coated prisms. As D is increased, the point of maximum doubling for the uncoated prisms as described before in Fig. 5 lies at large values of D. There is therefore a range of values of D lying between 0° and about 60° for which the diffraction patterns are sharper when the roof surfaces of the prisms are uncoated. For values of D larger than this, the prisms having silver-coated roof surfaces have the sharper diffraction patterns until the values of D approach 180°. For values of D near 180° (the values of D at which this takes place are still larger than 160° according to Fig. 5), the prisms with uncoated roof surfaces again have the sharper diffraction patterns. The angular doubling in the diffraction patterns for roof prisms with silver coated roof surfaces is for all values of D quite small.

5. CALCULATED FORMS OF DIFFRACTION PATTERNS FOR 90° DEVIATION AMICI ROOF PRISM

As has been suggested earlier, the particular prism for which we should like to make a careful quantitative comparison between theory and experiment is the 90° deviation Amici roof prism shown in Figs. 1 and 2. For this particular prism, the angle D is, of course, 90°. The experimental check of the theory will be done using the 5461 A.U. line of mercury so that n_g, n_m, and χ_m will have values corresponding to this wave-length. The prism used for the experimental check of the theory was made from borosilicate crown whose refractive index for the green mercury line is 1.5184. If now these values of n_g and D are substituted in Eq. (28), the diffraction pattern for an Amici roof prism with uncoated reflecting surfaces illuminated with plane polarized light of wave-length 5461 A.U. and incident azimuth angle α will be given by

$$J=(4ab)^2A_0^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\dfrac{V}{2}}{2\left(\dfrac{V}{2}\right)^2}$$

$$\times\{1+0.392759\cos V-(0.227767\cos 2\alpha$$

$$-0.080528\sin 2\alpha)\sin V\}. \quad (40)$$

The form of the diffraction pattern in the focal plane in a direction parallel to the roof edge (parallel to the horizontal direction in Fig. 3) as suggested earlier will be of the conventional Fraunhofer form for square apertures $\sin^2U/U^2$. A plot of the form of the intensity distribution described by this function is given in Fig. 9. It will be noted that all the ordinates of the curve have been multiplied by two and the same will also be done for all the curves which follow. The intensity of the first maximum on each side of the central maximum is about one-twentieth of the central maximum and the intensity itself vanishes at values of ξ on the photographic plate given by (see Eq. 12)

$$\xi=\frac{\lambda F}{2a}\cdot m. \quad m=1, 2, 3, \text{etc.}$$

In the V direction (perpendicular to the roof edge), the form of the diffraction pattern in the focal plane is a function of α. Since, as has been suggested earlier, this equation is not symmetric in V, the resultant pattern for all values of α except those given by Eq. (32) will not be symmetrical. The zero points in the pattern will be located at values of μ on the photographic plate given by

$$\mu=\frac{\lambda F}{b}\cdot n, \quad n=1, 2, 3, \text{etc.}$$

which if $a=b$ will be twice as far apart as those in the ξ direction. If one plots the part of J in Eq. (40) which is dependent on V (again with all ordinates multiplied by two), the forms of the diffraction patterns obtained for values of $\alpha=0°$, 20°, 45°, 70°, 90°, 110°, 135°, and 160° will be those shown in Fig. 10. These patterns have been mounted one above the other so that the changes in form with α can be readily seen. As compared with Fig. 9, these maxima have been lowered from two down to about 1.4. The central maxima of these curves are also all broader than that of Fig. 9 and the secondary bands twice as broad. The changes in the form of the pattern with varying α consist of an oscillation in form back and forth about the zero position of V with a period of 180° in α. All of the detailed changes in these curves have been reproduced photographically.

The form of the diffraction pattern for a 90° deviation Amici roof prism with uncoated reflecting surfaces illuminated with unpolarized light is given by Eq. (30). If the previously suggested values of D and n_0 are substituted in this equation, the resulting equation will be found to be equivalent to Eq. (40) with the $\sin V$ term absent. In unpolarized light, therefore, the pattern in the U-direction will be still that described by Fig. 9. If the part of Eq. (40) dependent on V (that is with the $\sin V$ term absent) is plotted for values of V between $-720°$ and $+720°$ (again with ordinate multiplied by two), Fig. 11 will be obtained. A comparison between the forms of the expected diffraction patterns in the two directions on the photographic plate when the prism is illuminated with unpolarized light of 5461 A.U. wave-length can, therefore, be obtained from Figs. 9 and 11.

To obtain the form of the diffraction pattern for the 90° deviation Amici roof prism illuminated with unpolarized light when its surfaces are coated with silver, we must return again to Eq. (33). For the Amici roof prism D is again 90° so that numerical substitutions for the sine and cosine terms involving D can be made without difficulty. Before any further numerical simplification can be made, the quantities i, ρ_s, ρ_p and Φ must be evaluated. The angle of incidence i on each of the roof surfaces from Eq. (27) is exactly 60°. Choosing the previously mentioned values for n_0, n_m and χ_m corresponding to the green line of mercury, these constants then have the values given by

$$n_0=1.5184, \quad n_m=0.530, \quad \chi_m=8.62.$$

Knowing these values for the optical constants, ρ_s, ρ_p and Φ can be evaluated from Eqs. (34), (35) and (36). They were found to have the following values (see also Figs. 6 and 7)

$$\rho_s=0.96749, \quad \rho_p=0.89042, \quad \Phi=226°30'34''.$$

All of the formerly unknown quantities are now known so that Eq. (33) can now be completely evaluated. After substitution of these various known quantities it

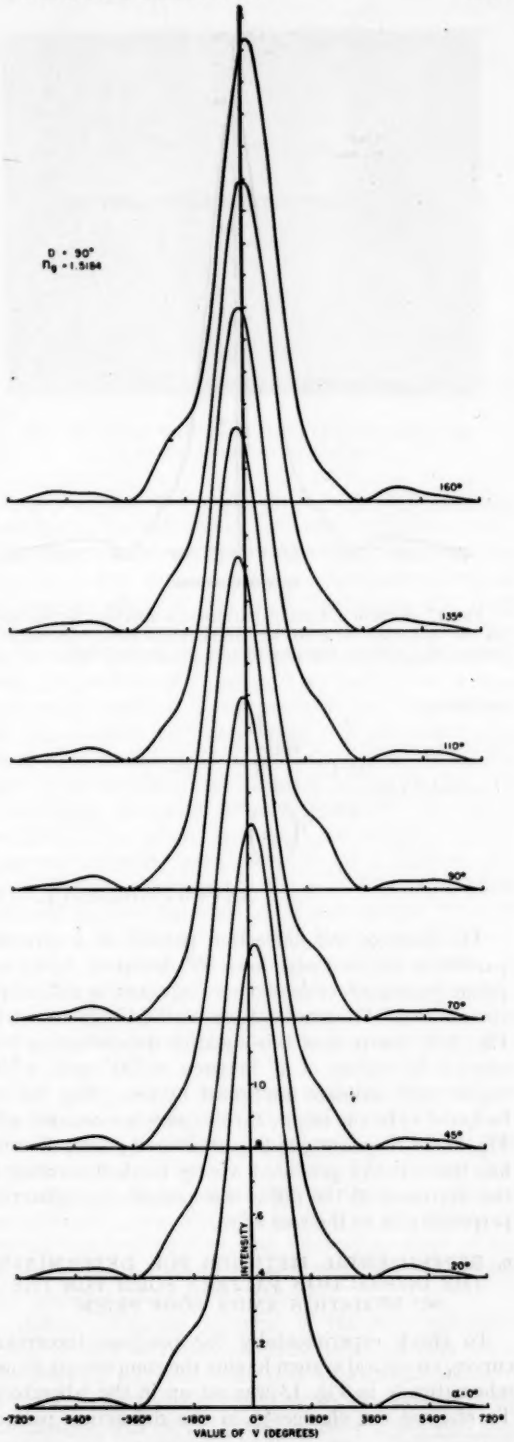


FIG. 10. Forms of diffraction patterns in a direction perpendicular to the roof edge for a 90° deviation Amici roof prism with uncoated roof surfaces illuminated with plane polarized light of different entering azimuth angles.

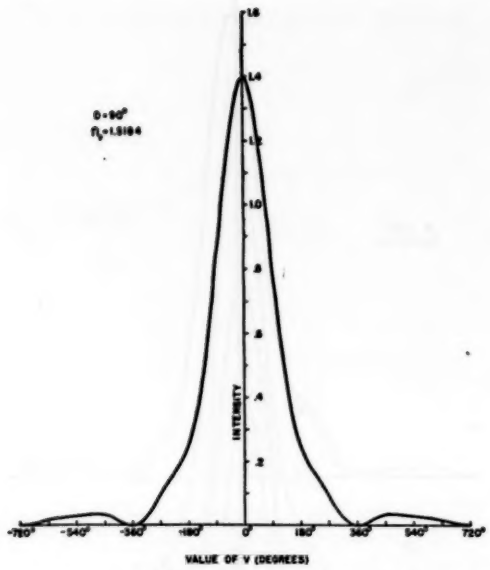


FIG. 11. Form of diffraction pattern in a direction perpendicular to the roof edge for a 90° deviation Amici roof prism with uncoated roof surfaces illuminated with unpolarized light.

becomes

$$J=(4ab)^2A_0^2\cdot\frac{\sin^2U}{U^2}\cdot\frac{\sin^2\frac{V}{2}}{2\left(\frac{V}{2}\right)^2}\times\{1+0.728702\cos V\}. \quad (41)$$

The form of the diffraction pattern in a direction parallel to the roof edge for a 90° deviation Amici roof prism having silver-coated roof surfaces is still of the conventional Fraunhofer form $\sin^2U/U^2$ described by Fig. 9. If the part of this equation dependent on V is plotted for values of V between $-720°$ and $+720°$ (again with ordinate multiplied by two), Fig. 12 will be found to be the result. If this figure is compared with Fig. 11 for the corresponding unsilvered prism, silvering has theoretically produced a very marked increase in the sharpness of the diffraction pattern in a direction perpendicular to the roof edge.

6. EXPERIMENTAL METHODS FOR DETERMINING THE DIFFRACTION PATTERN FORM FOR THE 90° DEVIATION AMICI ROOF PRISM

To check experimentally the previous theoretical curves, an optical system having the components shown schematically in Fig. 13 was set up in the laboratory. To observe the changes§§ in the diffraction pattern

§§ These changes in the diffraction pattern form for different azimuth angles α were shown in the form of a moving picture at the Annual Meeting of the Optical Society of America in New York City, March, 1948.

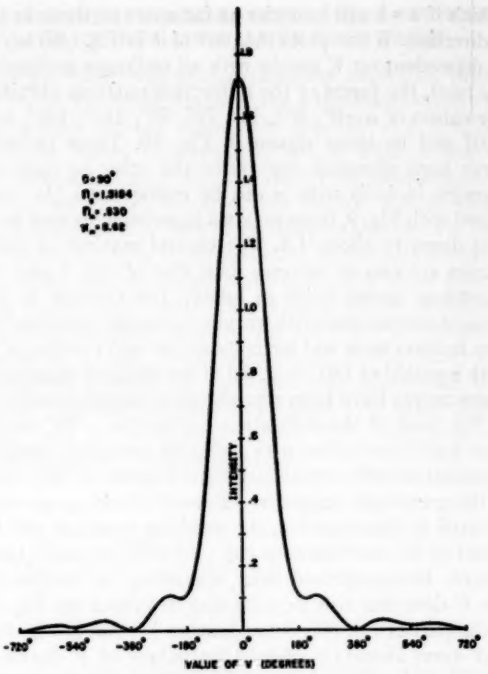


FIG. 12. Form of diffraction pattern in a direction perpendicular to the roof edge for a 90° deviation Amici roof prism having silver-coated roof surfaces and illuminated by unpolarized light.

form for plane polarized monochromatic light of changing azimuth angle when incident on a 90° deviation Amici roof prism having uncoated roof surfaces, an AH4 high pressure mercury arc source, rotatable polaroid and suitable filters for isolating the green 5461 A.U. line were placed in front of a 10 micron slit as indicated schematically at the upper left of Fig. 13. For making quantitative checks on the forms of the theoretical curves, this source later was replaced by a monochromator and a polarizing Glan Thomson nicol prism inserted in place of the polaroid. The light emerging from the slit in Fig. 13 was made parallel by the indicated collimator lens (492 mm E.F.) and then allowed to pass through the 90° deviation Amici roof prism in the direction indicated. In order to magnify

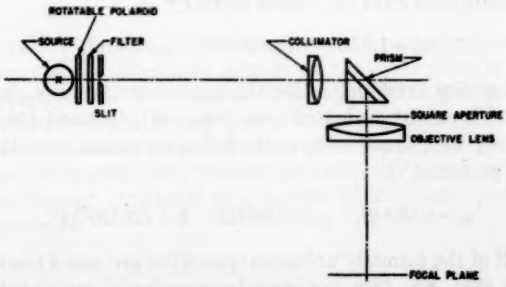


FIG. 13. Schematic diagram of optical system.

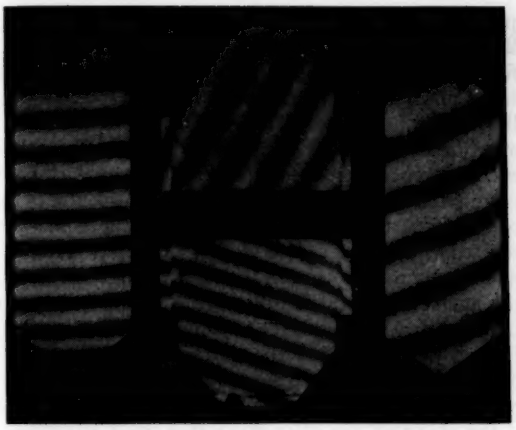


FIG. 14. Amici roof prism surface contour photographs.

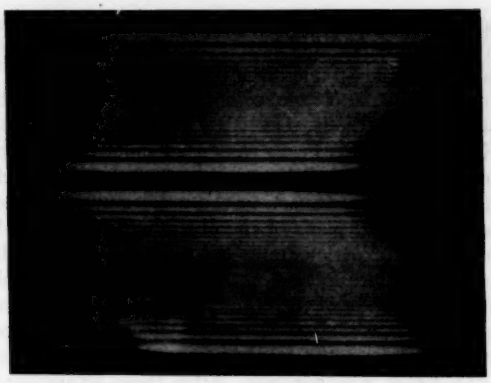


FIG. 15. Fresnel diffraction pattern of Amici roof prism in vicinity of restricting aperture.

the diffraction effects of the prism sufficiently so that they could be easily photographed, the light upon emerging from the prism at the right was restricted by a 5-mm square aperture centrally placed over the emergent prism aperture and was finally brought to a focus by a long focal length objective lens (3350 mm E.F.). In the focal plane of the focusing lens was placed a 35-mm camera with the lens removed so that the diffraction patterns could be recorded directly on 35-mm film. In the experimental arrangement suggested by Fig. 13, the mercury arc, monochromator, rotatable Glan Thomson polarizing prism, square aperture, objective lens and camera were mounted on two Gaertner optical benches which were placed on a single *L*-shaped supporting structure made from I beams. This supporting structure for the two optical benches was found to be necessary to eliminate building vibrations and other disturbances which affected the position of the diffraction pattern. Such an arrangement gave Fraunhofer patterns of the order of 0.4 mm between adjacent minima and other diffraction patterns perpendicular to the roof edge having separations of about twice this distance between adjacent minima. The finite width of the entrance slit broadens both patterns slightly and raises the minima slightly above the theoretically zero values in Figs. 9, 10, 11, and 12. To obtain the Fraunhofer pattern (see Fig. 9) characteristic of the direction parallel to the roof edge, the slit should have the orientation suggested directly by Fig. 13. To obtain the characteristic diffraction pattern in a direction perpendicular to the roof edge, the entrance slit in Fig. 13 must be rotated 90° about the axis of the collimating lens.

Obviously, before reliable diffraction patterns can be obtained, a high quality 90° deviation Amici roof prism had to be found. Several such prisms were obtained from the Optical Shop of the Naval Gun Factory and the best one chosen. In choosing the prism of highest quality, primary emphasis was placed on the accuracy of the roof angle. Since very little physical doubling of the diffraction pattern in a direction perpendicular to the roof edge exists in such prisms (see Fig. 11), a one hundred power auto-collimator with a micrometer eyepiece was used in making the final selections. The two prisms finally chosen showed no visible doubling of the auto-collimated image viewed with this one hundred power instrument. The prisms had wedge errors of about two minutes. The surfaces on these prisms had flatnesses|| || of the order of a tenth of a wave-length or better as evidenced by the surface contour diagrams indicated in Fig. 14.

Mounting the prism properly proved to be quite a problem. The prism assembly and square limiting aperture assembly were mounted on a common flat base. To accurately locate the roof edge in a plane parallel to this flat base, two machinist's *V*-blocks were used and the prism lightly but firmly held by a specially designed Lucite *C*-clamp. This system of mounting gave a strain-free prism whose entering and leaving faces were always perpendicular to the base plate making it easy to remove and reinsert the prism in its proper place.

The 5-mm square restricting aperture suggested by Fig. 13 was made from a unilateral slit with two razor blades mounted at right angles to the slit jaws. The square aperture assembly was mounted on a standard height gauge. The relative height of the square aperture with respect to the roof edge could then be adjusted by sliding the assembly on the vertical member of the height gauge. A final adjustment could be accomplished by using the micrometer screw.

Before diffraction patterns of the form computed could be obtained experimentally, the apparatus had to be properly adjusted. The first adjustment necessary was the location of the center of the slit and axis of the collimating lens in the plane containing the roof edge and the normals to the entering and leaving faces of the

|| || These photographs were taken by Donald Lowe of the Physical Optics Division of the Naval Ordnance Laboratory.

roof prism. This was accomplished by the use of an auxiliary height gauge. After this height adjustment was made, the 10-micron entrance slit was located in the focal plane of the collimating lens using auto-collimating methods. The Glan Thomson polarization prism was rotated in its calibrated mounting so that the azimuth angle of the entering plane polarized light was known with respect to the previously mentioned plane. The focal plane of the objective lens in Fig. 13 was located experimentally by inserting an optically flat front surface mirror in place of the prism and observing the image of the entrance slit with a ten-power eyepiece. To minimize diffraction effects during these focusing adjustments, the square aperture indicated in the figure was removed. After these adjustments were made, the square restricting aperture was reinserted in its proper place and the diffraction pattern observed and photographed. The intensity distribution within these diffraction patterns when later checked quantitatively was found to be of the Fraunhofer form suggested by Fig. 9.

The prism was next placed in its proper position shown schematically in Fig. 13 and auto-collimation methods again used to be sure its entering surface was normal to the axis of the collimating lens. The adjustment of the square aperture with respect to the roof edge of the prism had to be done with great care in order that the conditions of the problem suggested by Fig. 3 be met experimentally and the correct form of diffraction pattern in a direction perpendicular to the roof edge obtained. To be sure that the roof edge of the prism was parallel to the upper and lower edges of the square restricting aperture and simultaneously parallel with the slit, the out of focus Fresnel diffraction pattern shown in Fig. 15 was viewed with an eyepiece in back of the objective lens.¶¶ When these three were all properly parallel, this diffraction pattern appeared with lines of maximum contrast as shown in the figure. The final adjustment of the square aperture which then had to be made was that of being sure that the roof edge lies in the horizontal plane which bisects the square aperture as suggested by Fig. 3. Obviously, in Fig. 15 such was not the case for the center of the dark band corresponding to the roof edge is not in the center of the complete pattern. To bring the plane containing the roof edge into the center of the square aperture, the micrometer adjustment on the height gauge supporting the aperture had to be utilized to set the aperture so that the dark band in Fig. 15 lies in the middle of the Fresnel pattern. When the diffraction pattern in unpolarized light in a direction perpendicular to the roof edge was observed with an eyepiece in the focal plane of the objective lens after this rather crude adjustment

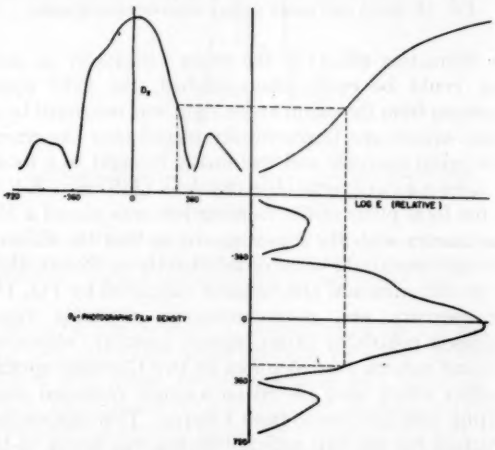


FIG. 17. Method of converting microphotometered diffraction pattern to log-E pattern.

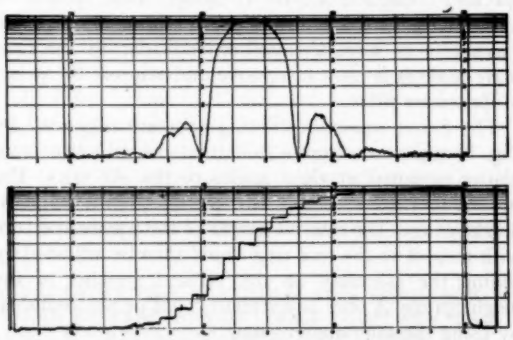


FIG. 16. A typical microphotometer trace of a diffraction pattern and density calibration.

of the aperture height, it was usually found to be non-symmetric in the outer band system. To remove this non-symmetry, small additional adjustments on the height were made with the micrometer adjustment. If the diffraction patterns in a direction perpendicular to the roof edge were photographed and microphotometered after making these adjustments, they were usually found to be symmetric as suggested by Fig. 11 and, hence, corresponded to the diffraction pattern resulting from two apertures of equal area of the form shown in Fig. 3. For obtaining good reproducible patterns, it was also found necessary to at all times keep the prism surfaces as clean as possible.

Due to the ratio of the focal lengths of the objective and collimating lens, the one inch length of the entrance slit was magnified about six times in the focal plane of the objective lens. Since light from different positions along the entrance slit after collimation enters the prism at other than normal incidence producing a different angular deviation D at the roof

¶¶ When the roof surfaces of the prism are silvered, the diffraction bands in the center of the pattern appear but with weaker contrast indicating that the phase relations between the upper and lower halves of the aperture are such that the two regions interact somewhat so that the complete pattern tends to be more characteristic of the Fresnel pattern for the complete aperture rather than that for two independent apertures.

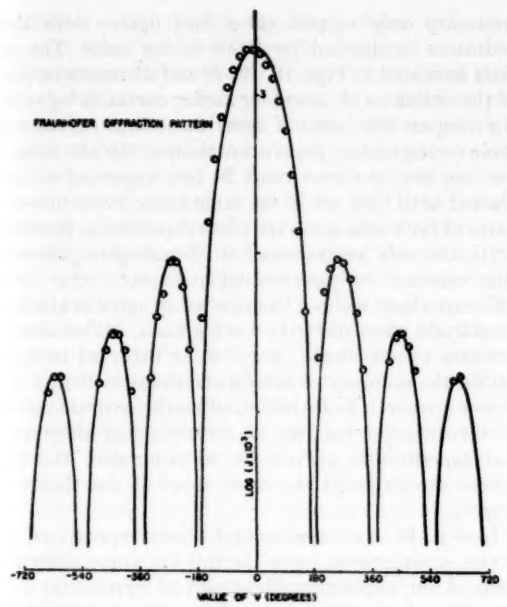


FIG. 18. Experimental and theoretical forms of Fraunhofer pattern plotted on log basis.

edge, the intensity distribution in the diffraction pattern corresponding to different points along the entrance slit will change slowly. In order to be able to photograph and microphotometer the resulting diffraction pattern at the point corresponding to the center of the entrance slit, a fine wire was placed across the middle of the entrance slit. The shadow of this wire was centered in the photograph of the diffraction pattern and microphotometer tracings made in the immediate vicinity of this shadow.

On each film with the photographs of the diffraction pattern was placed a density calibration. This was obtained by rotating the monochromator and light source about a vertical axis until the monochromatic light emerging from the exit slit was centered on the camera mount. The camera was then replaced by a mounted printing frame in which a calibrated density tablet was held in contact with a strip from the same roll of film on which the diffraction patterns were recorded. The entrance and exit slits of the monochromator were opened sufficiently to permit the correct exposure to be made. The exposure times for both the diffraction pattern and density calibration were made the same so as to eliminate any errors caused by reciprocity failure. To check the uniformity of illumination across the region of the step tablet, a piece of film was exposed and the resulting density after development microphotometered. The final diffraction pattern and its corresponding density calibration were simultaneously brush developed to minimize errors due to the Eberhard Effect, localized exhaustion of developer and other film errors. It was necessary to develop the films to a lower gamma than is normal for the film since the range of the Leeds and Northrup microdensitometer used for these measurements extended only to 1.7. A photograph of a typical microphotometer trace of a diffraction pattern in a direction

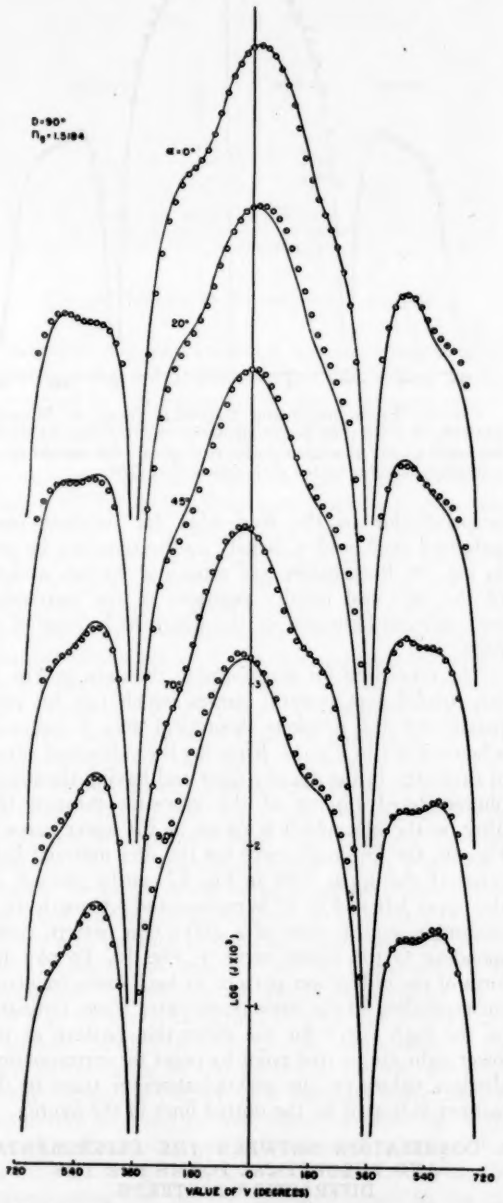


FIG. 19. Experimental and theoretical forms of diffraction patterns in a direction perpendicular to the roof edge plotted on log basis for 90° deviation Amici roof prism with uncoated roof surfaces when illuminated with plane polarized light of entering azimuth angles α.

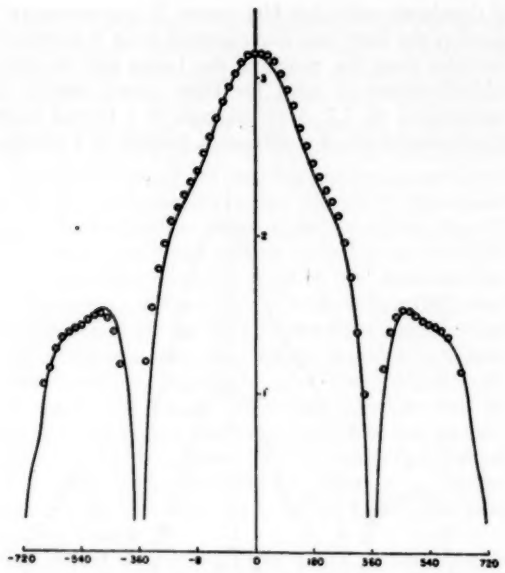


FIG. 20. Experimental and theoretical forms of diffraction patterns in a direction perpendicular to the roof edge plotted on log basis for 90° deviation Amici roof prism with uncoated roof surfaces when illuminated with unpolarized light.

perpendicular to the roof edge for incident plane polarized light and a density calibration can be seen in Fig. 16. Both before and after a given run, a check of the zero and infinity positions of the instrument are made as indicated in the figure to be sure of no drift.

The procedure for transforming the data in Fig. 16 into useful experimental curves which can be compared with the previous theoretical ones is indicated schematically in Fig. 17. Knowing the calibrated values of each step in the density filter and having the microphotometered tracing of the exposure through this filter on the film which is shown as the lower curve in Fig. 16, the $D-\log E$ curve for the film material indicated at the upper right in Fig. 17 can be plotted. At the upper left in Fig. 17 is represented schematically a microphotometric trace of a diffraction pattern corresponding to the upper curve in Fig. 16. To plot the form of the diffraction pattern in $\log E$ units (relative) corresponding to the microphotometer trace, ordinates on the $\log E$ curve for the diffraction pattern at the lower right are plotted point by point for corresponding abscissa values on the microphotometer trace in the manner indicated by the dotted lines in the figure.

7. CORRELATION BETWEEN THE EXPERIMENTAL AND THEORETICAL FORMS FOR THE DIFFRACTION PATTERNS

To bring the theoretical curves for the diffraction patterns in Figs. 9, 10, 11 and 12 into a form which can be compared quantitatively with the experimental curves for the diffraction patterns in $\log E$ units, it is necessary only to plot these four figures with their ordinates (multiplied by 1000) in log units. The full lines indicated in Figs. 18, 19, 20 and 21 represent plots of the ordinates of these four earlier curves in log units. To compare the forms of these theoretical curves with their corresponding experimental ones, the abscissas of the two sets of curves must be first expanded or contracted until they are in the same units. Since the ordinates of both sets of curves when expressed in intensity units are only proportional to the absolute intensity (the constant of proportionality in each case being different), they will not be expected to agree in absolute magnitude when plotted on a log basis. Differences in ordinate values should, however, be expected to agree within the accuracy of the experimental method if the theory is correct. If, therefore, either the central maxima or the adjacent maxima of corresponding theoretical and experimental curves are superimposed, the two curves should be of the same shape if the theory is correct.

In Fig. 18, the experimental points represented by circles superimposed upon the full line curve show the form of the experimentally observed Fraunhofer pattern. The forms of the two curves agree quite well. The peaks of the experimentally found curve, however, are somewhat broader than the corresponding theoretical curve. This broadening can be attributed largely to the finite size of the initial entrance slit. If the agreement between the experimental and theoretical curves for the other diffraction patterns in a direction perpendicular to the roof edge is of the same order of

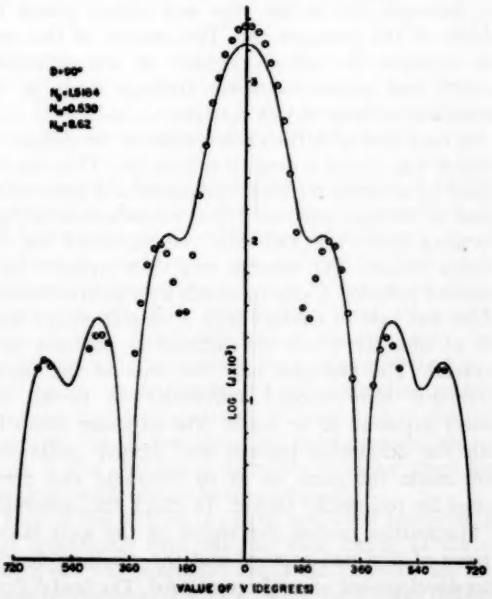


FIG. 21. Experimental and theoretical forms of the diffraction patterns in a direction perpendicular to the roof edge plotted on a log basis for the 90° deviation Amici roof prism with silver-coated roof surfaces when illuminated with unpolarized light.

magnitude, the theory describing these diffraction patterns was considered to be correct.

The agreement between the experimental and theoretical diffraction pattern forms in a direction perpendicular to the roof edge for plane polarized light entering a 90° deviation Amici roof prism with uncoated roof surfaces is shown in Fig. 19. Since these patterns repeat themselves with a period of 180° in α and the sequence of the patterns in the second half of the cycle is simply a reversal of the sequence of the patterns in the first half (see Fig. 10), it was felt that if the forms of the patterns over half the cycle were checked this would be sufficient to check the theory. In Fig. 19, the patterns for $\alpha=0°$, 20°, 45°, 70°, and 90° are, therefore, the only ones from Fig. 10 which have been plotted on a log basis. The agreement between the positions of the maxima for the two sets of curves is of the same order of magnitude as those in Fig. 18. The superimposed circles, although showing all the general changes in shape predicted by the theoretical curves, again represent a diffraction pattern which is somewhat broader.

A corresponding plot of the theoretical and experimental forms of the diffraction patterns on a log basis in a direction perpendicular to the roof edge when the 90° deviation Amici roof prism is illuminated with unpolarized light and the roof surfaces are uncoated is shown in Fig. 20. The agreement between theory and experiment is again of about the same order of magnitude as that for the Fraunhofer pattern in Fig. 18, the experimental curve again being somewhat broader.

Figure 21 shows the agreement obtained between the theoretical and experimental diffraction pattern forms in a direction perpendicular to the roof edge when the roof surfaces of the 90° deviation Amici roof prism were coated with silver and the prism illuminated with unpolarized light. The agreement is not as good as that between the two Fraunhofer patterns in Fig. 18. We feel, however, that this difference in forms of the two curves may be due to possible discrepancies between the optical constants of the silver film on the prism and those given by Tate. The films on the prism also were covered with a plastic preservative and a black paint to prevent oxidation and these might also have affected the optical constants of the films. The values of the optical constants for evaporated films were also used in Eq. (33), but the agreement was less satisfactory than that indicated in Fig. 21. At present Eq. (33) at least points in the general direction of the experimental results.

The diffraction pattern forms discussed in this paper for one good Amici 90° deviation roof prism were also photographed and analyzed for a second similar prism. The agreement between the theoretical curves and experimental points for this second prism were found to be substantially the same as those shown in Figs. 18, 19, 20 and 21. These curves were not, therefore, included in the present paper.

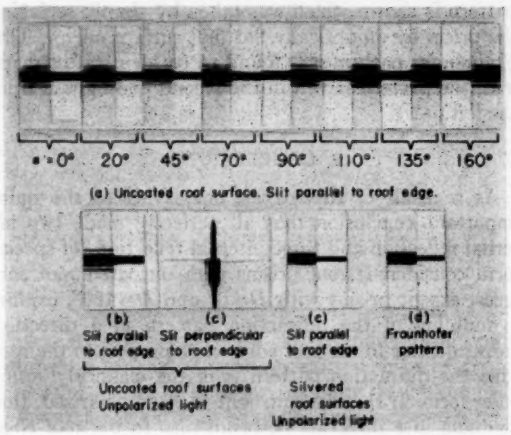

α=0° 20° 45° 70° 90° 110° 135° 160°
(a) Uncoated roof surface. Slit parallel to roof edge.
(b) Slit parallel to roof edge
(c) Slit perpendicular to roof edge
(c) Slit parallel to roof edge
(d) Fraunhofer pattern
Uncoated roof surfaces Unpolarized light
Silvered roof surfaces Unpolarized light

FIG. 22. Photographs of the diffraction patterns.

In the last Fig. 22 an attempt has been made to show pictures of the diffraction patterns themselves. In the upper part of the figure are shown a series of photographs of diffraction patterns mounted side by side so as to show the changes in the shapes of the diffraction patterns in a direction perpendicular to the roof edge when a 90° deviation Amici roof prism with uncoated roof surfaces is illuminated with plane polarized light of different entering azimuth angles. It will be noted that there are apparently two different sets of bands undergoing changes simultaneously. In taking these photographs, half of the length of the 10 micron slit (parallel to the plane of Fig. 13) was covered with a neutral density filter so as to reduce the intensity of the light in one-half of the image as compared to that in the other half. This filter makes it possible to observe simultaneously the changes in the central band structure as well as the structure of more distant bands from the center. The changes which take place in the photographs are not too pronounced but if they are observed carefully, some of the changes predicted by Fig. 10 can be seen. At the lower left in the figure are shown photographs of the diffraction patterns in directions perpendicular and parallel to the roof edge when the prism has uncoated roof surfaces and is illuminated with unpolarized light. These patterns as suggested by Fig. 9 and Fig. 11 are symmetrical in both the central and secondary band structure. In the photograph to the right in the lower central part of the figure, the form of the diffraction pattern in a direction perpendicular to the roof edge can be seen when the prism has silver coated roof surfaces and is illuminated with unpolarized light. This photograph when compared with the corresponding one for the uncoated prism to the extreme left shows a sharper central band and the secondary bands are now twice as numerous. This is again in agreement with Figs. 11 and 12. At the lower right in the figure a photograph of the Fraunhofer

pattern is shown which was taken by simply replacing the prism by an optically flat first surface mirror. This Fraunhofer pattern was found to be identical in shape with the pattern shown in the second photograph from the left.

8. CONCLUSIONS

As a result of this paper, one is led to the quite important conclusion that all perfectly made two internal reflection and three internal reflection (of special form considered) roof prisms with uncoated roof surfaces, except prisms with $D=0°$ and $D=180°$, exhibit a doubling of the diffraction pattern in a direction perpendicular to the roof edge while parallel to the roof edge the diffraction pattern is of the classical Fraunhofer form. If the incident light is plane polarized, this doubling in a direction perpendicular to the roof edge is in general unsymmetric while for incident unpolarized light it becomes symmetric. The forms of both types of diffraction patterns for each prism can now be calculated from a knowledge of the *angular deviation at the roof edge*, the *prism refractive index* and the *incident azimuth angle* of the plane polarized light if the prism is illuminated with plane polarized light. Silvering the roof surfaces of these prisms, except for prisms near $D=0°$ and at or near $D=180°$, results in a decrease of the doubling in a direction perpendicular to the roof edge without affecting the sharpness of the Fraunhofer pattern in a direction parallel to the roof edge. The forms of these diffraction patterns for silver coated roof surfaces can also be calculated if in addition the *refractive index* and *absorption index* of the silver are known. The agreement between the calculated and experimentally observed curves for the 90° deviation Amici roof prism with silvered surfaces is not as good as are the corresponding curves for the uncoated prism. This may be due to the use of improper optical constants for the film or to a violation of the boundary conditions at the glass-silver surface. Equation (33) describing the forms of these diffraction patterns may even be in error because of the many possible pitfalls occurring in its development. The important point here, however, is that prisms of unfavorable geometry of the types described can be made quite useful by simply coating the reflecting roof surfaces with silver.

The only diffraction patterns whose forms can be calculated from this theory are those formed by rays which are parallel to the plane of Figs. 2 or 4. Nothing is known therefore about the diffraction pattern behavior if the rays are incident on the first prism surface at increasing angles with this plane. Whether or not silvering the roof surfaces of other types of roof prisms will improve their image quality cannot readily be stated. Other types of films may even prove more advantageous than silver.

Equation (33) as presented in this paper suggests another interesting application, namely, that of determining the optical constants of metals from a study of the forms of the diffraction patterns of roof prisms. Since reflection takes place at a glass-metal boundary, the metal would, itself, be free from the usual oxidation difficulties. Calculations from this formula are, however, more complicated than those usually necessary[5] and would not be advisable unless there was an interest in checking results by the two methods.

9. ACKNOWLEDGMENTS

The authors are indebted to several people who made contributions in one way or another to the preparation of this paper. The Optical Shop of the Naval Gun Factory was responsible for the making of the unusually fine prisms used in this work. The care which was exercised in making prisms of such high accuracy in the roof angle will only be appreciated if an attempt is made to duplicate them. Various groups within the Naval Ordnance Laboratory also made substantial contributions. The Analysis and Publication Division of the Laboratory were responsible for routine calculations, curve plotting and art work associated with the paper. The Photographic Division made all the photographic reproductions. Various other members of the Physical Optics Division helped from time to time in various phases of the work particularly E. H. Winger, who frequently helped in analyzing the experimental data. H. Osterberg of the American Optical Company made several suggestions in reviewing the paper before publication. Last but not least, the authors are personally indebted to Lumarilyn Satterfield who was very helpful in the actual writing of the paper and typed the paper in its preliminary and final form.

Errata

A list of errors or brief corrections to articles will be published in the December issue of the Journal in order that both the article and necessary corrections may be indexed in the same volume. Errata should be in the office of the Editor not later than November 15, except errata to the November issue which should be sent to the office of the Editor by December 1.

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 40, NUMBER 10 OCTOBER, 1950

A 72-Inch High Vacuum Evaporator and Its Glow Discharge Equipment

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(Received June 29, 1950)

This paper describes a 72-inch diameter high vacuum evaporator constructed primarily for applying silicon monoxide-protected aluminum coatings to 60-inch searchlight reflectors. Data are presented on studies made to determine the optimum shape, size, and position of glow discharge cathode for obtaining uniform heating and consequent cleaning of mirror forms. The experience gained from the studies made on glow discharge arrangements for the 72-inch evaporator was used in designing discharge arrangements for small coaters.

THE evaporator described below was constructed primarily for applying silicon monoxide-protected aluminum coatings to 60-inch searchlight reflectors. It is also practical for the economical mass production coating of smaller optics.

I. CONSTRUCTION AND OPERATION OF A 72-INCH EVAPORATOR

The coating chamber of the evaporator, pictured schematically in Fig. 1, is a vertical cylindrical steel tank made of rolled steel $\frac{3}{8}$ inch thick. The vertical section, which is 72 inches in diameter and 31 inches high, is capped on either end with standard convex "dished" tank heads having 3-inch straight flanges. The total height of the tank is 62 inches. This unusual size has made deviations from normal evaporator design necessary. Unlike conventional coating chambers, which have a bell-jar that can be raised and lowered, the tank remains stationary. The dished cover at the top is removable for inserting and removing reflector forms. The top of the tank projects through a second floor thus providing convenient working space for the operator. From this floor the operator can maneuver reflector forms and the cover into position with an electrically driven hoist. Three glass windows on the side and one on top of the tank enable the operator to view the interior and thus to control the evaporation process. Two flanged openings off-set from the center of the bottom serve as pump ports. A third flanged opening at the center of the bottom is fitted with a 24-inch diameter plate for supporting the evaporation sources.

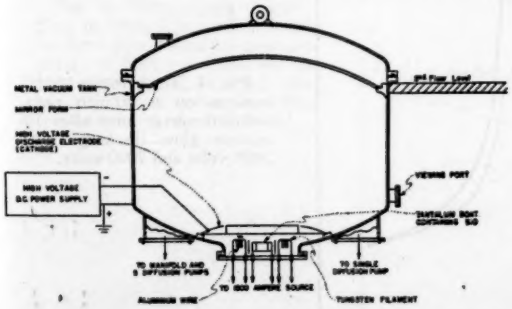

FIG. 1. Diagram of 72-inch evaporator.

This plate is mounted on a cart containing the power equipment for the evaporation sources and a reversible motor for raising or lowering the plate. When the plate is lowered, the cart can be pulled from under the tank, thus making the evaporation sources readily accessible to the operator for renewal.

The tank is evacuated with two Kinney DVD 8810 mechanical pumps and five Distillation Products Incorporated Type 500 MC oil diffusion pumps. Four of the diffusion pumps are attached to a single combination manifold and high vacuum valve which is kept closed during the glow discharge cleaning cycle. The fifth pump has its own high vacuum valve which is manually controlled to maintain the proper pressure in the tank during the glow discharge cycle.

The evaporation source for applying aluminum is so constructed that an opaque coating can be applied in a very short time (less than 20 seconds), since a fast evaporation of aluminum produces a more dense, compact coating. The evaporation of aluminum takes place from eight horizontal helically wound tungsten wire filaments connected in parallel. Each filament is formed from 62-mil diameter tungsten wire and consists of twelve loops, $\frac{7}{16}$ inch outside diameter, spaced $\frac{3}{16}$ inch. The evaporation source for applying a protective coating of silicon monoxide consists of a tantalum boat filled with small pieces of silicon monoxide. This boat is formed from a piece of sheet tantalum 9 inches by 4 inches by 0.008 inch. About 1000 amperes is required for heating the boat to the required temperature of about 1200°C.

It was found advantageous to evacuate the tank to coating pressure before the glow discharge in order to check the vacuum system and to reduce the time between the discharge and coating cycles. After the pressure in the tank is reduced to about 0.02 micron, the high vacuum valves are closed and air, or better still oxygen, is introduced by means of a needle valve until the pressure rises to a few microns. The glow discharge is more effective when the residual gas is air or oxygen.

The power supply for the glow discharge is capable of furnishing 15,000 volts at 500 milliamperes direct current. A 5000-ohm resistor in series with the cathode and rectifier stabilizes the discharge and prevents overload-

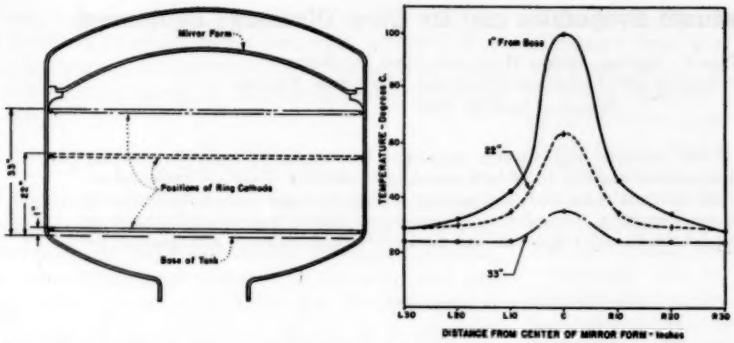

FIG. 2. Temperature distributions on a 60-inch paraboloidal mirror form after 10-minute glow discharge with 5000 volts and 300 ma from a 60-inch diameter ring cathode in three vertical positions.

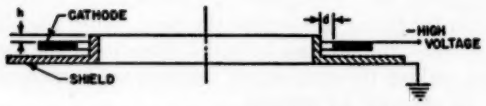

FIG. 3. Diagram showing the cross section of a ring cathode with shield. *h* denotes the distance the shield protrudes above the cathode and *d* denotes the distance from cathode to shield.

ing of the power unit. The glow discharge cathode consists of an aluminum ring, seven inches wide, with a convex surface that parallels the concave contour of the 60-inch reflector to be coated. A cylindrical shield grounded to the tank prevents the cathode from being coated with the evaporated materials and prevents excessive heating at the center of the reflector form. A glow discharge produced with 6000 volts at 500 milliamperes for 10 minutes is usually sufficient. The above glow discharge arrangement was adopted after studies of tests of a number of designs and arrangements.

II. THE EFFECT OF VARIOUS GLOW DISCHARGE ARRANGEMENTS

The effectiveness of the glow discharge produced by various arrangements was determined by measuring the temperature created in a given time at various zones on a 60-inch reflector form. This was done by attaching thermocouples to the center of 4- by 4-inch glass plates placed on a form having the same size and shape as a 60-inch searchlight reflector. The plates were placed at the center of the form and at the 10, 20, and 30 inch zones on four sides of the center.

A ring 60 inches in diameter, made from $\frac{5}{8}$-inch diameter aluminum rod, was tested in three positions. The current and voltage of the discharge and the pressure within the tank were the same for the tests made at each position. Figure 2 shows the positions occupied by the ring cathode and the corresponding temperatures attained at the end of 10 minutes discharge. For each position of the cathode the heating was poorly distributed, being very high at the center and low at the 30 inch zone. The strongest bombardment of the mirror form occurs when the cathode is placed close to the base of the tank.

A study was made of the heating effect produced by the glow discharge when large flat cathodes were used. Aluminum disks four and five feet in diameter with 22 inch holes in the center were tested near the base of the tank. The concentration of heat on the center of the mirror form was even more pronounced than when a ring cathode was used. Better energy distribution was

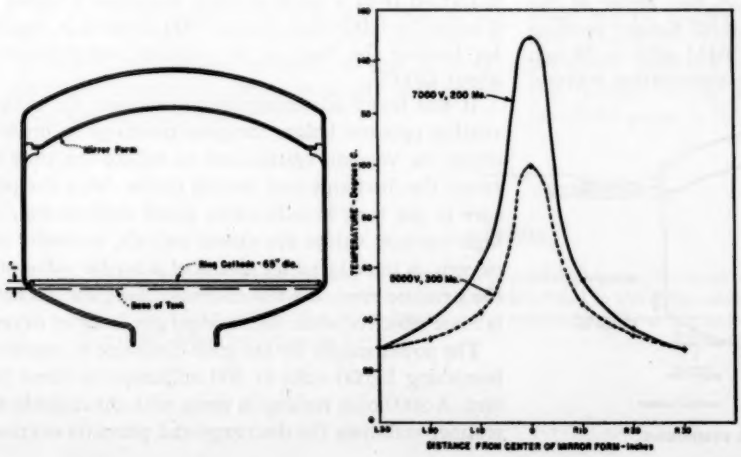
Mirror Form
Ring Cathode - 65" dia.
Base of Tank
7000 V, 200 Ma.
5000V, 300 Ma.
TEMPERATURE - Degrees C.
DISTANCE FROM CENTER OF MIRROR FORM - Inches

FIG. 4. Temperature distributions on a 60-inch paraboloidal mirror form after 10-minute glow discharge with 5000 volts and 7000 volts.

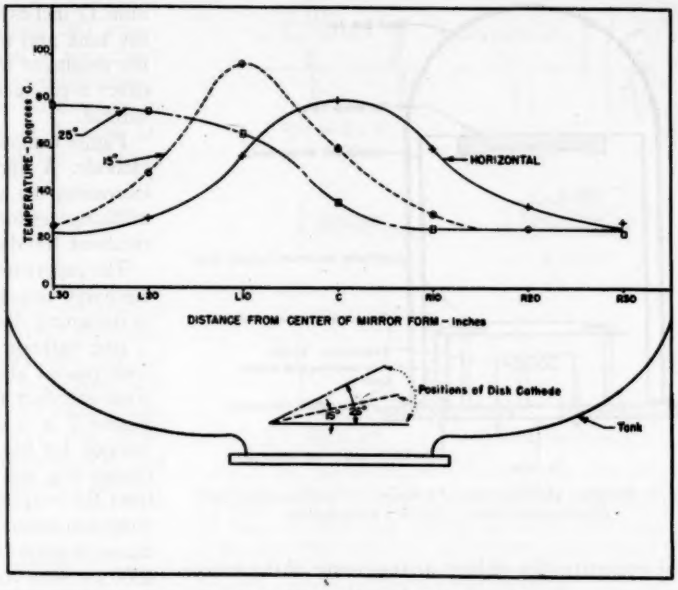

FIG. 5. Temperature distributions on a 60-inch paraboloidal mirror form after 10-minute glow discharge at 5000 volts and 300 ma from disk cathode placed horizontally and tilted at 15 and 25 degrees.

achieved by placing a grounded cylindrical shield inside the opening of the ring cathode as shown by Fig. 3. The horizontal section of the shield prevents the cathode from being coated and is not necessary if the cathode is near the base of the tank. The distribution of heat on the mirror form is greatly affected by the position of the cylindrical shield with respect to the cathode. In Fig. 3, h denotes the distance the shield protrudes above the cathode and d denotes the distance from cathode to shield. For a discharge produced with a given current and voltage, increasing d without changing h tends to concentrate the discharge to the center of the mirror form. Conversely, increasing h without changing d tends to direct more of the energy to the periphery of the mirror form. Nominal value of h and d are $\frac{3}{8}$ in. to 1 in. In order to obtain uniform heating of the mirror form with a discharge of a given current and voltage it is necessary to determine the correct position of the shield with respect to the cathode and to arrange the cathode, shield, and mirror form symmetrically.

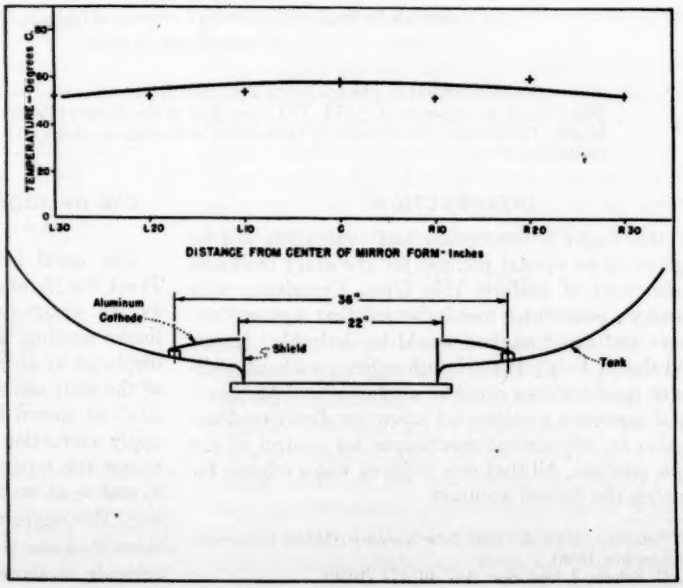

FIG. 6. Temperature distributions on 60-inch paraboloidal mirror form after 10-minute glow discharge at 6000 volts and 400 ma from adopted cathode (ring cathode with convex surface paralleling concave surface of mirror form).

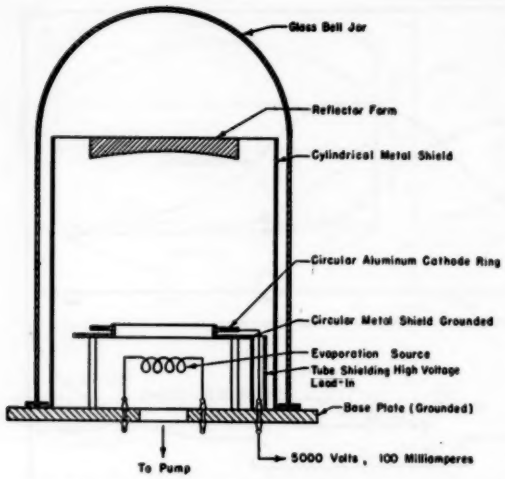

FIG. 7. Diagram showing glow discharge cathode arrangement developed for use in 18-inch evaporator.

The concentration of heat at the center of the mirror form becomes more pronounced as the voltage of the discharge is increased. This is illustrated in Fig. 4.

To study the effect of the shape of the cathode on energy distribution, a disk cathode of flat sheet aluminum 17 inches in diameter was placed near the base of the tank and tested at various angles. Figure 5 shows the results of the tests. Note that the greatest heating effect is produced in a direction normal to the cathode surface.

Figure 6 shows the results obtained with the adopted cathode. A higher temperature may be obtained by increasing the voltage. A 10-kilovolt discharge at 400 milliamperes for 10 minutes will heat the mirror surface to about 100 degrees C.

The experience gained from the studies made on glow discharge arrangements for the 72-inch coater was used in designing discharge arrangements for small coaters. A ring cathode 9 inches inside diameter and one inch wide placed about 6 inches above the base plate has given satisfactory results in an 18-inch diameter coater. Figure 7 is a diagram showing the arrangement developed for use in a small evaporator. The glow discharge ring and high voltage lead-in, which is shielded from the evaporation sources, stays clean thus yielding more consistent results. For evaporators using 18-inch diameter glass bell jars, a 5- to 10-minute discharge at 4000 to 5000 volts and 75 to 100 milliamperes is sufficient. In order to prevent excessive heating of a glass bell jar during the glow discharge cycle, it is desirable to install a heat-conducting cylindrical metal shield just inside the evaporator.

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An Interferometric Method for Accurate Thickness Measurements of Thin Evaporated Films

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A method is described in which a Fabry-Perot interferometer is used to measure the thickness of uniform thin films to an accuracy of ±15A. The separation of the *D*-lines of sodium light is used as a standard of length. The method is evaluated by comparison with other methods and in terms of its applications and limitations.

INTRODUCTION

IN this paper a description and evaluation will be given of an optical method for the exact thickness measurement of uniform thin films. Experience with Tolansky's procedures had indicated that a more convenient and rapid method would be desirable.[1] It was found that a Fabry-Perot interferometer without additions or modifications could be used directly.[2] Mechanically it possesses a calibrated screw for direct readings and also an adjustment mechanism for control of the sample position. All that was required was a scheme for obtaining the desired accuracy.

[1] S. Tolansky, *Multiple-Beam Interferometry* (Oxford University Press, London, 1948).
[2] L. G. Schulz, J. Opt. Soc. Am. **40**, 177 (1950).

USE OF SODIUM LIGHT WITH A FABRY-PEROT INTERFEROMETER

The usual interference fringes given by a Fabry-Perot interferometer are circular with radii increasing as the square-root of integers. Because of this nonlinear spacing, when one part of a fringe system is displaced by an extra deposit d, as in Fig. 1A, the extent of the shift cannot be determined directly by the ratio S/R, as shown in Fig. 1B. Although it is possible to apply correction factors, it is much more convenient to use the separation of the two sodium wave-lengths λ_1 and λ_2 as an internal standard in the following manner: The instrument is calibrated by finding the positions I of the screw at which the two sets of fringes coincide, as shown in Fig. 1, drawing B. The separation

K (see drawing E) between any two such positions is equal to $(\lambda_1\lambda_2)/2(\lambda_1-\lambda_2)$, which is about 500 wave-lengths. When the separation is decreased by the extent M_x from a I position to a II position, the fringes change to the pattern of drawing C. Likewise an increase in separation of M_y leads to the pattern in drawing D. The working equation for finding the thickness, T, of the deposit is then simply

$$T=\frac{(M_x+M_y)\lambda}{4K}. \qquad (1)$$

where λ is equal to $(\lambda_1+\lambda_2)/2$. The reason for measuring both M_x and M_y and then taking one-half of their sum is that positions II and III can be set with greater accuracy than can position I. This procedure also tends to minimize a small source of error which will be discussed later. Obviously to the observer the fringe configuration of II is identical with that of III. The two can be distinguished by starting from an initial I position.

OPTIMUM WORKING CONDITIONS

Experience showed that the observer's eye is best placed at a distance of ten to fifteen cm from the mirror surfaces. The fringe system, however, appears to be formed at infinity. If the human eye is to see clearly both the fringes (at infinity) and the step edges on the samples (at ten to fifteen cm) it is necessary to increase the depth of focus of the eye. This was conveniently done through the use of a circular limiting aperture 0.5 mm in diameter formed in a thin metal sheet. Observations were made by holding this sheet before the eye and viewing the field through the hole.

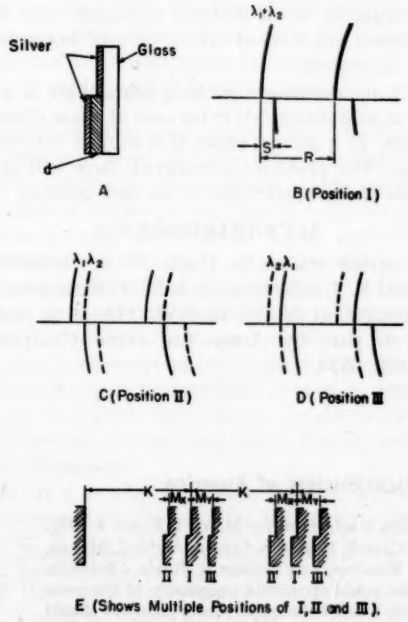

FIG. 1. Drawings showing the fringe configurations for measurements with sodium light. In drawing B the fringe systems for λ_1 and λ_2 are in coincidence; in C and D they are separated. Drawing E shows the sequence in which positions I, II, and III appear repeatedly as the mirror separation is increased. The best working range is for separations smaller than $2K$.

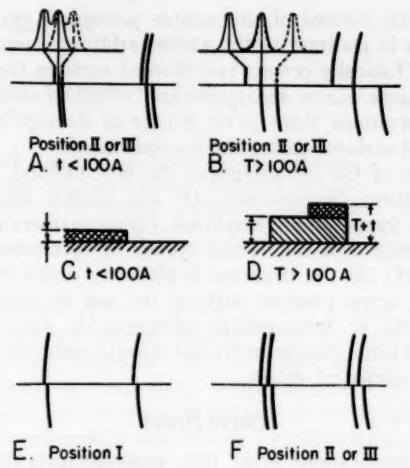

FIG. 2. The case of thicknesses t smaller than 100A. Drawing A shows the intensity contours for $t<100$A; drawing B is for $T>100$A. In each case the solid curve refers to the fringes above the horizontal step edge whereas the broken line refers to the fringes below this edge. In C and D is shown the manner of combining a small thickness t with a larger one T. Drawings E and F illustrate a second method of fringe matching.

It is desirable that the mirrors be adjusted to exact parallelism but this is not essential. (For a complete discussion of the effect of non-parallelism see Tolansky,[1] page 14.) A change in separation of one wave-length per inch can be tolerated. Likewise good mirror surfaces produce the sharpest fringes but an error of one wave-length per inch is permissible.

Because of the high intensity of commercial sodium vapor lamps it was found possible to use silver thicknesses up to 600A. The resulting fringe width was then about 1/20th of a fringe separation. Positions II and III could be set to 1/10th fringe width, thereby leading to an accuracy of $(1/200)(\lambda/2)$ or $\pm$15A. By averaging several readings this could be reduced to $\pm$5A.

EVALUATION

The new method is almost a conventional use of a Fabry-Perot interferometer except that an internal measuring unit has been added. A comparison with Tolansky's procedure reveals these differences: Whereas Tolansky uses small mirror separations (of the order of a few wave-lengths) with the mirrors at not necessarily parallel positions, the new method employing a Fabry-Perot interferometer involves large mirror separations (of the order of 500 wave-lengths) with the mirrors at close to exact parallelism. With a Fabry-Perot inter-

ferometer control of the sample position is retained. This is in contrast to the almost arbitrary manner in which Tolansky presses two silvered surfaces together. With large mirror separation and complete control of their positions there is no danger of damage to the silvered surfaces during the measurements.

Most of the advantages of the new method result from these conveniences: (1) the readily available sodium vapor lamp is employed; (2) no auxiliary equipment such as a collimating system or spectrometer is required; (3) the thickness is given by direct reading of the screw position without the use of correction equations or intermediary photographic steps. The method is not only sensitive but is also capable of giving actual numerical values.

LIMITATIONS

For applications other than measurements on uniform films of controlled thickness it is necessary to point out several limitations of the new method:

1. For the exact alignment of the fringes in positions *II* and *III* it is necessary that the center of the fringes be well defined. This is not the case for thicknesses t less than 100A (or for $N\lambda/2\pm t$ where N is an integer) as is shown schematically in Fig. 2A. A possible way of avoiding the limitation is to follow the procedure suggested in drawings C and D: a thickness $t<100$A to be measured is placed over a thickness $T>100$A. This procedure, however, involves two measurements, therefore a greater error. In addition, it may not be feasible to place the layers as shown. (Fig. 3A of the following paper[3] shows the procedure applied to silver films.)

An easier way of extending the useable range to lower thicknesses is to use the method of fringe matching shown in Fig. 2F. One of the rings above a step edge is set to bisect the separation of the two rings below, and vice versa. Because of the small thicknesses being considered the three intervals cut off by a group of four closely spaced rings may be considered as equal in size. The working equation for calculating the thickness T becomes

$$T=\frac{(M_x+M_y)\lambda}{8K}. \tag{2}$$

K, M_x, and M_y are now associated respectively with positions *I*, *II*, and *III* of Fig. 2E and F, in the same way as in Fig. 1. With this second method of matching thicknesses in the range of 150A down to 60A can be accurately measured. Below 60A it is possible to estimate the thickness to $\pm$20A.

2. A slight limitation in the ultimate accuracy of the new method results from the fact that the rings do not have exactly the same size for two different separations of the reflecting surfaces. For example, referring to Fig. 1, if the deposit d is one wave-length thick and the separation K is 500 wave-lengths, the corresponding rings to be matched differ in size by about 0.2 percent. In practice the resulting error is reduced to about 0.02 percent by measuring both M_x and M_y for corresponding rings. For very large thicknesses this error becomes proportionally larger.

3. The method, of course, only measures fractional parts of half wave-lengths. A multiline source, such as an unfiltered mercury arc, can be used to obtain the number of half wave-lengths. Also the white-light fringes of a Michelson interferometer might be used.

4. Because of the large separation of the mirrors the family of rays producing a fringe arises from considerable area. It is therefore necessary that the material being measured be of uniform thickness. Also for the same reason this method cannot be used in conjunction with a microscope.

In all measurements on thin films there is a great danger of misinterpretation because of phase changes on reflection. In a second paper this subject is considered in detail. The problems considered there will serve as examples of the application of the new method.

ACKNOWLEDGMENTS

The author wishes to thank C. S. Barrett, John Platt, and E. J. Scheibner for helpful discussions during the development of this method. This work was supported in part by Army Air Force Contract No. AF33(038)-6534.

[3] L. G. Schulz and E. J. Scheibner, J. Opt. Soc. Am. (to be published).

Washington, D. C., Meeting of the Optical Society of America

The Washington, D. C. Meeting of the Optical Society of America is scheduled for March 1, 2, and 3, 1951. The program committee consisting of Stanley S. Ballard, Burt H. Carroll, Kasson S. Gibson, Archie I. Mahan, Dorothy Nickerson, Henry O'Bryan, Richard Tousey, Robert A. Woodson, and Wallace R. Brode, *Chairman*, has been appointed by President William Meggers. The committee would appreciate suggestions of symposia subjects, and suggestions of invited papers, contributors, or subjects. Contributed papers from members should be submitted on the abstract form which will be mailed to all members with an announcement of the meeting. Contributed papers may be presented by non-members who should send requests to the program chairman or the Society secretary for proper abstract forms. The Washington meeting coincides with the 50th anniversary of the founding of the National Bureau of Standards and this anniversary will be suitably recognized at the meeting.

A New Photometric Device

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(Received June 29, 1950)

Two photometric devices are described. Each of these devices employs modulated tungsten filament lamps. In the first the lamps are electrically independent of the detector. In the second a feed-back arrangement is used. These devices should prove useful for transmission or reflection measurements of neutral or colored materials.

INTRODUCTION

MODULATED or flickering beams of light have been used by a number of persons interested in photometric devices. Various instruments employing mechanical or electrical means for producing flickering beams of light have been described by Hardy,[1,2] Duntley and Tyler,[3] Murcek,[4] Hood,[5] Dimmick,[6] Wright and Herscher,[7] White and Liston,[8] and by others.

The system of modulated lamps described before the Optical Society by Duntley in 1941[9] and the densitomiter described at the same meeting by Duntley and Tyler[3] represented an attempt to provide a photometric system having the advantages of the photometer described by Hardy[2] in combination with a greatly simplified optical system.

The densitometer was admirably suited to the measurement of transmittance or reflectance of substantially neutral materials but, because of the discharge-type lamps, could not very well be used for color densitometry or abridged spectrophotometry.

PRINCIPLE OF OPERATION

A system of modulated lamps similar to Duntley's which does not seem to have been described in the literature consists of two tungsten lamps having fine wire filaments connected as shown in Fig. 1. In this circuit each lamp receives an equal and constant alternating component from the transformer, and a direct component which is equal to or greater than the peak value of the alternating component. The two lamps will thus flicker at the frequency supplied to the transformer but in opposite phase. A photo-tube placed so as to receive equal illumination from each lamp will detect no flicker of the primary frequency, but will detect, however, a spurious signal having twice the primary frequency.

There are a number of reasons for this. The heating and cooling rates of the tungsten filament are different, the relation between light output and voltage is nonlinear and the spectral distribution of the light at the two voltage limits is different. These effects can be minimized by employing lamps designed for rapid cooling of the filament, by working at low frequencies, and high filament temperatures, by using narrow bandpass filters and so forth.

Another photometric circuit is shown in Fig. 2. In this circuit the alternating component supplied to the lamps is derived from the state of unbalance of the two beams. If the photo-tube is receiving equal illumination from each lamp a slight spurious oscillation of the

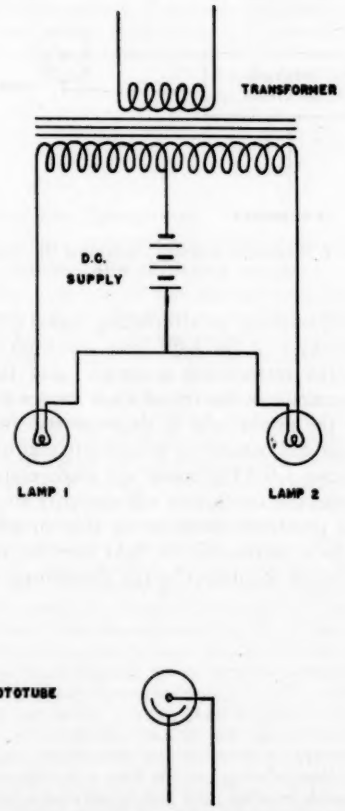

FIG. 1. Schematic diagram illustrating the modulated tungsten lamp device.

[1] A. C. Hardy, J. Opt. Soc. Am. **18**, 96 (1929).
[2] A. C. Hardy, J. Opt. Soc. Am. **25**, 305 (1935).
[3] S. Q. Duntley and J. E. Tyler, J. Opt. Soc. Am. **31**, 461A (1941).
[4] Murcek, U. S. Pat. No. 2,282,198 (May 5, 1942).
[5] Hood, U. S. Pat. No. 2,376,311 (May 15, 1945).
[6] Dimmick, U. S. Pat. No. 2,474,098 (June 21, 1949).
[7] N. Wright and L. W. Herscher, J. Opt. Soc. Am. **37**, 211 (1947).
[8] J. U. White and M. D. Liston, J. Opt. Soc. Am. **40**, 29 (1950).
[9] S. Q. Duntley, J. Opt. Soc. Am. **31**, 460A (1941).

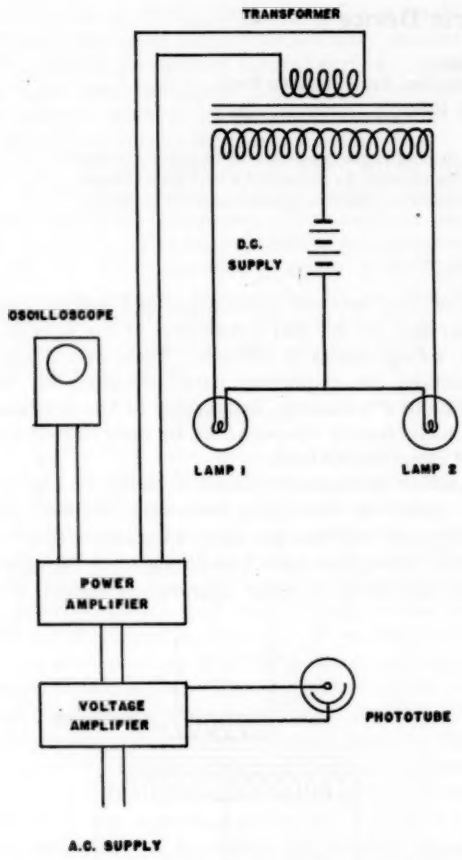

FIG. 2. Schematic diagram illustrating the modulated tungsten lamp device with feed-back.

lamps will produce no alternating signal at the photo-tube. However, if the light from one bulb is suddenly reduced (by introducing a sample) and the resulting surge of current in the transformer causes the *combined* light on the photo-tube to decrease still further, then this circuit will commence to oscillate and will continue in oscillation until the beams are made equal again, at which point the oscillation will abruptly stop.

In the practical operation of this circuit it is also possible for a decrease in the light from one bulb to give rise to a surge of current in the transformer which will cause the *combined* light on the photo-tube to increase (instead of decrease as before). Under these conditions one would expect that the circuit would be prevented from oscillating. It is our experience, however, that in the absence of deliberate frequency control oscillation will occur in this case too, but the frequency is approximately double that of the former case.

In this connection it should be mentioned that if the balance point is approached first from one side and then from the other, the instrument will not register the same balance point reading. This would indicate that for small differences in beam intensity in the out-of-phase sense the circuit is indeed prevented from oscillating.

DISCUSSION

An interesting feature of the feed-back photometric circuit of Fig. 2 is that as the balance point is approached the amplitude of the a.c. component becomes smaller and the effects of differences in filament heating and cooling rates, of color temperature, and of non-linearity of light output with voltage become less significant, until finally at the balance point these effects disappear altogether leaving the lamps on the d.c. supply only. The endpoint is quite critical and can be easily reproduced to within 0.02 in the value of density.

Since this circuit becomes unstable when the level of illumination from the lamps is too high, and since the precision of setting of the balance point is affected by the level of illumination, it has been found desirable to use an optical system in which the sample and comparison wedge are in the same beam. In this way the illumination on the photo-tube is always the same at balance and the precision of setting the balance point is maintained at approximately the same level.

Although at the present time these two devices have been used only in instruments for densitometry, there seems to be no logical reason why they cannot be used also in other photometric applications including spectrophotometry and colorimetry providing the lamps can be adequately controlled. This should not be too difficult a problem since the filament currents can be easily and independently controlled and, if desirable, both filaments can be mounted in the same envelope.

The author wishes to express his appreciation to F. W. Dunne who assisted in the construction of these devices.

Book Reviews

Atlas der Restlinien

ALOIS GATTERER AND JOSEPH JUNKES.

Vol. I. **Spektren von 30 chemischen Elementen** contains 28 photographic charts 30×40 cm, and 53 pp. of descriptive text and wave-length tables. 1st Edition 1937, 2nd Edition 1947. Specola Vaticana. Price $15.00.

Vol. II. **Spektren der Seltenen Erden** contains 45 photographic charts, 30×40 cm, and 350 pp. of descriptive text and wave-length tables for 18 elements. Specola Vaticana, 1945. Price $45.00.

Vol. III. **Spektren seltener Metalle und einiger Metalloide** contains 42 photographic charts, 30×40 cm, and 80 pp. descriptive text and wave-length tables for 25 elements. Specola Vaticana, 1949. Price $25.00.

The first attempt to provide a comprehensive atlas of atomic spectra was made in 1905 by Hagenbach and Konen whose *Atlas der Emissionspektren* gave heliographic positive reproductions of 28 charts of arc, spark and flame spectra (2500 to 6500A) of 68 elements. The spectra were photographed with a Rowland grating of one meter radius ruled with 20,000 lines per inch, and all wave-lengths in the accompanying text were limited to four figures.

The second major contribution of this kind was the *Atlas Typischer Spektren* issued in 1911 by Eder and Valenta who gave heliographic negative reproductions of 53 charts of the spectra of 72 elements photographed with grating-, glass-, and quartz spectrographs. Four-figure values of wave-lengths were printed for principal lines in the charts and supplementary tables contained five- or six-figure values of several thousand lines, all on the Rowland scale which was displaced shortly thereafter by the present International scale.

All former atlases of spectra are now eclipsed by the *Atlas der Restlinien* prepared, 1937 to 1949, by Gatterer and Junkes at the Astrophysical Laboratory of the Vatican Observatory. This reviewer has mentioned the earlier works primarily to provide a basis for appraisal of the recent work. Without meaning to disparage the earlier works, which were outstanding in their time, it may be said that this recent work exhibits more points of contrast than of comparison with the earlier.

The *Atlas der Restlinien* consists of three voluptuous volumes, each containing photographic charts and wave-length tables of prismatic arc and spark spectra of 70 elements. Because this undertaking was inspired by the collection of meteorites in the Vatican Observatory, Volume I was dedicated to 30 elements usually detected in ferrous and stony meteorites, *viz.* Ag, Al, As, Au, B, Ba, Bi, C, Ca, Cd, Co, Cr, Cu, Mg, Mn, Mo, Ni, P, Pb, Pt, Rb, Sb, Si, Sn, Sr, Ti, Tl, V, W, Zn, with arc spectra ranging from 2200 to 5900A, and spark spectra from 2200 to 4000A. In addition arc spectra of eleven elements (Ba, Ca, Co, Cr, Mn, Mo, Ni, Rb, Sr, Ti, V) were shown from 5800 to 8000A. Accompanying wave-length tables were restricted to strong lines marked on the 28 charts. This volume proved so popular that the exhausted 1937 Edition was followed by a revised second edition in 1947. Volume II was devoted to 45 charts of arc and spark spectra of 18 elements, *viz.* Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sc, Sm, Tb, Th, Tm, Y, Yb, Zr. The arc spectra range from 2265 to 7600A, the spark spectra from 2265 to 4530A. The wave-length tables of Volume II contain about 40,000 lines, nearly 10,000 of which are new in spectroscopic literature.

Volume III contains 42 charts of the arc and spark spectra (2100 to 6340A) of 19 metals, *viz.* Au, As, Be, Ga, Ge, Hf, In, Ir, Nb, Os, Pd, Pt, Re, Rh, Ru, Sb, Ta, Te, U, and high frequency excitation spectra (2340 to 6430A) of six elements, *viz.* Cl, Br, I, S, Se, Hg. The wave-length tables in this volume list 4775 lines.

The spectral charts in this *Atlas der Restlinien* are not mechanical reproductions; they are photographic negatives made on excellent quality double-weight paper. The average dispersion, resolving power and detail far surpass anything heretofore available to spectroscopists in general. Each spectrum is shown in triplicate with weak, medium and strong exposures, each of which is accompanied by an iron-arc spectrum, by an engraved scale of wave-lengths, and by engraved wave-lengths of the principal lines. The wave-lengths are given to six figures on the modern International scale although most of them are quoted from other sources. In the wave-length tables visual estimates of intensities of spectral lines are given on a scale of 1 to 20, and the successive spectrum to which each line belongs is indicated when this information is available. Abridged tables of the stronger "analysis" lines are presented for each chemical element and additional tables containing "impurity" lines or discrepancies among different observers are often included.

Because this Atlas was designed for spectrochemical identification the analysis lines were meticulously selected and experimentally verified. In general the supplementary tables of spectral lines are far from complete but they include all the stronger lines and exclude all false lines due to impurities or ghosts. These corrections and omissions as well as the addition of 10,000 lines to rare-earth spectra constitute concrete contributions to spectroscopic science; they improve the data both by subtraction and by addition, and give the applied spectroscopist increased confidence in the infallibility of chemical identification by means of optical spectra. This *Atlas der Restlinien* is truly a monumental publication, an outstanding example of exquisite typography, a superb collection of spectral charts and tables, an indispensible reference work for all spectroscopic laboratories.

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Analytical Absorption Spectroscopy.

M. G. MELLON, Editor. John Wiley and Sons, Inc., New York, 1950. Pp. 618+vii. Price $9.00.

This excellent collection of nine monographs belongs in the second category of the classification: textbook, compendium, encyclopedia. The chapter headings and the respective authors are: 1. "Preparation of Systems" 77 pp. (M. L. Moss). 2. "General Principles" 39 pp. (M. G. Mellon). 3. "Color Comparimeters" 45 pp. (W. B. Fortune). 4. "Filter Photometers" 25 pp. (R. H. Müller). 5. "Spectrophotometers" 82 pp. (K. S. Gibson). 6. "Photographic Methods" 38 pp. (E. R. Holiday). 7. Applications, Ultraviolet and Visual" 133 pp. (E. I. Stearns). 8. "Spectrophotometers, Infrared" 76 pp. (L. J. Brady). 9. "Measurement and Spectification of Color" 86 pp. (D. B. Judd). The format and illustrations are good and the work is free of typographical errors.

It is always difficult in a work of this type to achieve proper balance between the elementary and the advanced. In fact one may almost define a compendium as a work which requires a textbook and a periodical library to go with it. The fact that one chapter presents 574 references, largely to the original literature, illustrates the point. Along the same line, the experimental directions given in some chapters are so terse as to require further reference yet long and numerous enough to add considerably to the size and cost of the volume. These criticisms, however, are meant more for the species than for the example at hand. The editor and contributors have achieved what is perhaps as good a balance as possible in a work of this type; the reader is given a broad, authoritative view of each field, sufficient detail to decide what further study is required, and is provided with a profusion of carefully chosen references.

The first chapter includes a table of selected photometric methods for the determination of inorganic and organic constituents. This is a most valuable guide to the practicing analyst. The perennial problem of units and their definition is discussed at some length in several chapters. The graphs indicating various methods of plotting spectrophotometric curves are particularly interesting, as are the response curves for various types of photoelectric devices. Chapter 7 contains a very clear discussion of additive absorbancies.

The book as a whole suffers from those disadvantages which are inevitable in a collection of monographs dealing with closely related subjects. It is hard to locate certain topics even with the help of an excellent index because they are scattered throughout the book. Some methods or devices are largely overlooked, for example, the Cary recording spectrophotometer. Others such as the Philpot-Schuster instrument are given perhaps undue emphasis.

These criticisms may be overlooked, however, in view of the value of the contents. The work is broad in scope and authoritative. It constitutes a significant contribution to the field of absorption spectroscopy and will undoubtedly be used widely.

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Spectrochemical Procedures.

CHARLES E. HARVEY. Applied Research Laboratories, Glendale, California, 1950. Pp. 402+x. Price $7.50.

A refreshing and authoritative discussion on qualitative and quantitative emission analysis with particular emphasis on the applied aspects. As the author points out in his introduction he has avoided the "cook-book" style in preference for a discussion of the reasons why certain steps and procedures must be taken and has left it to the reader to adapt these principles to his equipment, material to be analyzed and analytical requirements of precision and range. Although published by one of the leading manufacturers of spectrochemical analytical equipment, the author maintains an impartial position with regard to equipment so that the text is equally important to all workers whether they have been equipped by the sponsor or other manufacturers. Thus considerable prestige is accorded the discussion.

In addition to the extended sections on qualitative and quantitative analysis, there is also a section on "semiquantitative" analysis. This is a field in which the author has previously published a text and one in which he writes with the authority of considerable practical experience. The development of tables on the extraneous effect of anion and cation combination of the sensitivity of lines of weaker intensity than the persistent lines provides the basis of a method which has been extended to more precise determinations by incorporation with some other methods such as total energy, visual comparison with standards and combination with line pairs or step sector pairs of equal intensity and use of the background as an internal standard.

The introduction to quantitative procedures is well described by a consideration of the basic principles, standard methods of calculation, and variables affecting the analysis. Quantitative procedures are considered under metals and alloys, foil, wire and turnings, non-metallic samples, solutions and microsamples. Supplementary topics include maximum sensitivity methods, major constituent determinations, unusual elements, and direct reading procedures. A brief discussion of the design and operation of a spectrochemical laboratory concludes the text. The book is a distinct contribution to the art and will find a welcome audience in most spectrochemical laboratories.

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Washington, D. C.

Hydrogen in Chemical Atoms.

WILLIAM MAYO VENABLE. Markowitz, Haas, and Kopelman, Pittsburgh, Pennsylvania, 1950. Pp. 156+vi. Price $4.00.

The author of this book reveals a most uncritical appraisal of spectroscopic work. He does not seem to appreciate the significance of the beautifully confirmed Hund theory of atomic spectra and the present detailed knowledge of the interpretation of molecular spectra; and ignores the essential laboratory procedure of observing spectra. His postulate stated on page 5 is "The analyses presented in this monograph indicate that the development of all 'atomic' spectra of the first, second, and third orders requires hydrogen in the atmosphere of the arc, spark, or flame from which the lines are emitted." He then explains apparent discrepancies in the interval separations found among atomic lines as due to the presence of molecular lines of hydrogen. He intermingles atomic and molecular lines at will and comes out with a spurious array of interval separations which he regards as fundamental evidence that "The analyses presented . . . indicate that hydrogen is a dissociation product of lithium, nitrogen, and oxygen but not of beryllium, boron, or carbon. First- and second-order spectra of beryllium, boron, or carbon cannot be excited in materials supplied by any one of those elements alone, in the pure state, but require hydrogen from some other element which must also be present in the excitation tube or the flame."

His discussion of solar lines is also misleading; he reports that the most intense line of Li I has been observed as a faint line in the spot spectrum, not reported as present in the reversing layer. In 1928 (Carnegie Inst. Wash. Publ. No. 396) this line was reported as *strong* in the spot spectrum. Later (Carnegie Inst. Wash. Publ. No. 579) both lines of this doublet were reported as present but faint in the disk spectrum but *not faint* in the spot spectrum. He states that the behavior of Li in the sun "requires the presence of Sub 3, both isotopes of Sub 2 and hydrogen"; whereas the ionization potential derived from the long series observed in the laboratory atomic spectrum provides the correct explanation.

The reviewer regrets that careful scientific spectroscopic work which has contributed so much to our knowledge of atomic structure has been subjected to such treatment.

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Color Psychology and Color Therapy.

FABER BIRREN. McGraw-Hill Book Company, Inc., New York, 1950. Pp. 284. Price $4.50.

Mr. Birren has written an interesting and worth-while book. Its subtitle, "A factual account of the influence of color on human life" describes its contents somewhat more accurately than does its main title. The work is divided about equally in four parts or "Aspects": Historical, Biological, Psychological, and Visual. In the course of the four parts he at least touches on nearly all the possible relations which exist among color, vision, and life. He considers the subject very broadly, not confining himself to visible light but, in the Biological Aspects at least, treating extensively of the effects of both ultraviolet and infra-red. From these effects he reasons that, although less is known about the specific effects of visual light, they must be there since light is necessary for human beings.

The author having slanted the book toward medicine in the main title and in the preface—"I am convinced that a fair appraisal of color will restore its prestige in the eyes of modern medicine and will lead to great human benefits"—the reader will be somewhat disappointed by the small amount of careful research that has been done in this direction. The purpose in writing the book, in fact, was to encourage such research.

In the first section dealing with the Historical phase the reader finds a scholarly and painstaking analysis of the whole history of the claims that have been made for color. He concludes this section by deploring the fact that because of extravagant claims and charlatanry in the past, serious-minded workers have hesitated to do research in this field. Few people who have not read this first section or Mr. Birren's previous works can realize the extent to which the public's interest in color has been "worked for all it was worth."

Biological Aspects cover the effect of radiant energy on plant and animal life, with an impressive chapter on the Invertebrates and Vertebrates. There is a chapter on the diagnosis of physical and mental disease by means of color. In another he reviews the work of the few people who have seriously considered color for its therapeutic value. As the crux of this part of the work, the reader will be somewhat disheartened by the small amount of evidence produced and wish that more work might be done under more scientific control.

In the section called Psychological Aspects he considers the emotional reactions of individuals to color, the effect of color on neurotics and psychotics. He then goes on to consider psychological associations with colors and the subject of color harmony and color preference, ending with a chapter called "This Illusory World." Psychologists will probably take exception to treatment of such subjects as lightness constancy and illumination perception as illusions and mysteries, just as physiologists will probably object in the previous chapter to classifying the sensation of light produced by pressure on the eyeball in the same manner.

In the final section on Visual Aspects he gives a review of the subjects of vision and seeing, concluding with a chapter covering the economic value of color in industry and its use in many other situations, and a chapter called "Prescription of Color" in which he makes specific recommendations for specific situations. Mr. Birren's many years as a successful color consultant show clearly in these last chapters which are the most rewarding in the book.

The present reviewer found the book both stimulating and interesting. He somewhat disagrees with the author's constant insistence that the subject is mysterious and "anomalous." It tends to make one discount his claim at the end of Chapter 5 that the remainder of the book will consider the subject ". . . not in an obscure or mystical way, but from a more sober and objective viewpoint." Color Constancy would not appear to be either magic nor an illusion from the known facts.

No one will disagree with his final conclusion, however, "It is not enough to believe in the virtues of color; orderly and diligent research is needed to clarify its therapeutic values and develop reliable techniques for its use."

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JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 40, NUMBER 10 OCTOBER, 1950

International Optical News

London Meeting of the International Commission of Optics

The second formal meeting of the International Commission of Optics was held on July 17, 18, and 21, 1950, under the presidency of Thomas Smith of England. Most of the sessions were held in the very pleasant environment provided by the rooms of the Royal Society in Burlington House. It was apparent to the delegates who had attended the meeting held two years ago in Delft, Holland, or the preparatory meetings held earlier in Prague and in Paris, that the nature of these gatherings was undergoing a definite change. The earlier activities had been concentrated around the interchange of information on the progress in the various technical fields of optics which had occurred since the onset of World War II. It appears that this period of "catching up" has now come to an end, since there has been ample opportunity for optical scientists of the various nations to inform one another of war-time and postwar technical advances. At the London meeting, therefore, more attention was given to planning the future activities of the commission. In addition to the very valuable function of fostering international colloquies and other scientific gatherings, it was agreed that there are certain other items which are appropriate for international study and action. Among these are the general problem of classification, either under the universal decimal classification used in many scientific periodicals or some other scheme. The International Commission of Optics proposes to cooperate with the International Federation of Documentation in bringing out a revised classification for optics. It was felt strongly that an effort should be made to work toward the adoption of a recommended set of symbols and sign conventions for geometrical optics, and this program is now under way. Of course it is understood, realistically, that the several cooperating nations can never be *forced* to accept such proposals. Recommended procedures will hence be circulated among the national committees for comment and perhaps for acceptance, in principle or in fact. Certainly any progress in this direction, however small it may be, will be generally beneficial and of practical importance. Another item was the preparation of a recommendation for some standardization of the methods employed in measurements made in physiological optics, the purpose here being to facilitate the comparison of data obtained in different laboratories and in different countries. A further subject which was discussed was the possibility of working out a widely acceptable set of test methods and standards for the quality of optical glass.

It is now understood that future meetings of the commission will not give much time to the presentation of progress reports or review papers on miscellaneous optical subjects, but will be concerned with recommendations for action along lines of international importance, and the holding of special colloquies on specified subjects. It is hoped that the commission can sponsor such colloquies, perhaps as often as annually, in addition to those which are planned to coincide with the general congresses which will be held every second or third year. Among the topics suggested for discussion in the relatively near future are phase-contrast microscopy, new optical materials, spectroscopic instruments (including interferometers), aspheric surfaces, and selected aspects of the broad field of physiological optics. It is expected that these colloquies will be small in size and that they will be attended only by specialists in the particular fields.

Another subject which received a great deal of discussion was the apparent need for an international, or perhaps an all-European, optical journal. It was agreed that the Journal of the Optical Society of America meets the needs of American optics in a highly

satisfactory manner, but that there is no European counterpart of this excellent journal. It was felt that there is a real need for a journal which will include important optical contributions from all of Europe, printing articles in either English or French, and that it will be of particular value to those countries which have no widely circulated optical journal. The convenience to American workers of having a single journal which will satisfactorily cover all important optical activities in Europe should be readily apparent. This subject will be studied with sympathetic interest by the various national committees, in the hope that a mutually acceptable decision can be reached in the not too distant future.

It was also agreed that close liaison should be maintained with other international organizations which deal with neighboring or borderline subjects, and liaison officers were appointed to the International Astronomical Union, the International Commission on Illumination, the Joint Commission on Spectroscopy, and the Congress of Photography.

Nine countries were represented at this meeting by official delegates: Belgium, France, Great Britain, Holland, Italy, Spain, Sweden, Switzerland, and the United States of America. The U.S. delegates were I. C. Gardner, R. Kingslake, and S. S. Ballard. No delegates were present from Czechoslovakia or Poland, although these countries have participated in former meetings. The following officers were elected to guide the commission until the completion of its next general congress: President, A. C. S. van Heel of the Technical University of Delft, Holland; Vice Presidents, L. C. Martin of Imperial College, London, J. M. Otero of the Optical Institute Daza de Valdes, of Madrid, Spain, and S. S. Ballard of Tufts College, Medford, Massachusetts. P. Fleury and A. Arnulf, both of the Institut d'Optique of Paris, continue to serve as secretary and treasurer respectively.

London Conference on Optical Instruments

This very successful conference was held in the auditorium of the Department of Physics of Imperial College, South Kensington, on July 19–26, 1950. The detailed preparations made by the organizing committee were abundantly evident through the business-like way the conference was run and the manner in which all the ancillary arrangements such as apparatus exhibits, soirées, and trips to optical firms and laboratories were handled. The total registration was about 250 and included representatives not only from the countries which participated in the I.C.O. meeting, but additionally from Denmark, Egypt, Finland, India, Israel, and Western Germany. The actual attendance at the various sessions appeared to vary around a mean of about 150. There was unmistakable evidence of real, continuing interest throughout the serious sessions which occupied five full days of meetings. Contributing factors to this successful "audience response" were the skillful grouping of papers of mutual interest, the selection of chairmen who were personally interested in the fields discussed, and the regular breaks for morning coffee and afternoon tea which were adhered to with Trojan courage by the several chairmen. A feature of special importance to the value of the conference was the long period made available for discussion after each symposium or set of papers. These discussion periods were regularly scheduled on the printed program; they contained the added feature of "invited contributions" which had been previously arranged, so as to permit the comments to be illustrated by lantern slides in some cases, and to show other advantageous signs of previous thought and preparation. In your reporter's opinion, this opportunity for adequate discussion was a major contributing factor to the great success of the conference.

It is not appropriate here to list the names of the various speakers and their specific topics. The manuscripts of the papers presented are being collected into a volume which will be published soon by Chapman and Hall, Ltd., and will be available in the U. S. from John Wiley and Sons, Inc. Some indication should be given, however, of the several topics which were selected for discussion. To quote from the program of the meeting: "The object of this conference is to obtain a survey of modern practice and trends in the construction of actual instruments and thus enable those attending more readily to appreciate the direction in which useful advance is likely. For this reason the organizers have not solicited papers in which the main interest is theoretical." In general, half-days were devoted to symposia on the following subjects, each symposium comprising three papers: reflecting microscopes, reflecting telescopes, phase-contrast microscopes, spectrophotometers, gratings and grating instruments, photographic and projection lenses. During the first two days of the conference, joint sessions were held with the International Commission of Optics, and papers on the following subjects were presented: diffraction in optical instruments, new optical materials (plastics, glasses, and crystals), and current developments in microscopy. The Royal Photographic Society and the Royal Astronomical Society held special evening meetings, but perhaps the outstanding evening event was a special reception for conference members at the Royal Institution which was followed by a discourse on phosphorescence with excellent experimental demonstrations given by the Director, Professor E. N. da Costa Andrade.

The interest taken in the various subjects was indicated, at least roughly, by the size of the audience, the intensity with which the papers were followed, and the amount of discussion which took place. Based on these criteria, it can be stated that there is a great deal of current interest in the employment of catadioptric systems both in microscopes and telescopes, and there are many scientists working on the design of these relatively new systems, and using them in diverse applications. The growing employment of the spectrophotometer as an industrial tool in the U. S., and to a lesser extent in England, was commented upon. The new echelle gratings developed in America were described for the first time to a British audience, and evoked much discussion. A high point of the "invited discussion" was the description of the new method of making plane diffraction gratings that has been devised by Sir Thomas Merton and is being developed at the National Physical Laboratory of England. Upon one-half of a polished metal cylinder is cut a helix having a pitch equal to that of the required grating, using a diamond tool on a suitably geared-down screw-cutting lathe of special construction that is substantially free from progressive errors in pitch. The helix is copied upon the other half of the cylinder in such a way as to eliminate its periodic errors: the corrected helix is impressed by a diamond guided from the original helix on the principle of the chasing lathe but using a guiding nut lined with strips of a soft elastic material such as cork. The corrected helix is coated with the solution of a suitable plastic which after hardening and annealing is removed from the cylinder as a thin pellicle and opened out, with the rulings down, upon a moist gelatin-coated plate of glass. When the gelatin has dried the pellicle can be stripped off, leaving the gelatin moulded into a plane grating which is then hardened and aluminized. An elaborate but elegant series of tests for the gratings thus obtained has been developed at the National Physical Laboratory. Not only are conventional optical means of examination such as the knife-edge test employed, but also special interferometric methods and moiré patterns. It appears that the new development is one which should be of very great interest to all those who are concerned with the manufacture of diffraction gratings.

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Alphabetical Directory of Members

(As of July 10, 1950)

The number in parenthesis following each name is the serial number in order of election to membership. It gives the reference to the original record of election in the Society's archives. The letter A indicates Associate Member; AC, Associate Corporation Member; AE, Associate Member Emeritus; AL, Associate Life Member; H, Honorary Member; R, Regular Member; RE, Regular Member Emeritus; RL, Regular Life Member; S, Student Member. The following table gives the serial number of the last member elected in the indicated calendar year.

Election year	Serial number	Election year	Serial number	Election year	Serial number
1916	74	1928	620	1939	1194
1917	87	1929	807	1940	1457
1918	100	1930	867	1941	1657
1919	131	1931	908	1942	1909
1920	203	1932	934	1943	2091
1921	301	1933	949	1944	2282
1922	362	1934	975	1945	2405
1923	404	1935	1021	1946	2575
1924	425	1936	1052	1947	2742
1925	466	1937	1112	1948	2922
1926	540	1938	1150	1949	3135
1927	553				

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YASEEN, GEORGE (2824 A), Lever Brothers Company, 1271 Indianapolis Blvd., Hammond, Ind.
YODER, ELWIN C. (2753 A), 321 North Loomis St., Naperville, Ill.
YONTS, OLIVER C. (2966 A), 119 West Vance Rd., Oak Ridge, Tenn.
YOUNG, CLINTON J. T. (1022 R), Melpar, Inc., 452 Swann Ave., Alexandria, Va.
YOUNG, F. MANSFIELD (2581 S), Room 8-203, M.I.T., Cambridge 39, Mass.
YOUNG, THEODORE R. (2957 A), 5713 Chillum Hts. Dr., Hyattsville, Md.
YOUNKIN, S. G. (3167 A), Campbell Soup Company, Riverton, N. J.
YOUNGKRANTZ, HOWARD R. (1548 A), Apex Smelting Company, 2537 West Taylor St., Chicago, Ill.

ZAVESKY, ROBERT J. (1927 A), National Carbon Company, Inc., Fostoria, Ohio
ZEEB, LAWRENCE E. (2924 A), 156 West Patterson Ave., Columbus 2, Ohio
ZIEGLER, GEORGE E. (1372 R), 6847 Cherry St., Kansas City 5, Mo.
ZIELER, HANS WOLFGANG (977 R), 4900 Marine Dr., Chicago, Ill.
ZIGLER, MICHAEL J. (1136 R), Wellesley College, Wellesley 81, Mass.
ZIMMERLY, RAY A. (2658 A), Columbia Steel Company, Pittsburg, Calif.
ZIMMERMAN, CARLTON F. (3079 A), Arner Company, Inc., Buffalo 3, N. Y.
ZINSZER, HARVEY A. (1141 A), Fort Hays Kansas State College, Hays, Kansas

Geographical Directory of Members

Members in the United States According to States and Towns

ALABAMA—7

Birmingham
Dotson, Clifford L.
Edge, James M.
Kennedy, William R.
MacKenzie, James T.
White, Lock, Jr.

University
Barr, E. Scott
Creitz, Ellis E.

ARIZONA—2

Phoenix
Lyon, Lloyd F.

Tucson
Perillo, F. J.

CALIFORNIA—120

Altadena
Perry, Donald M.
Angwin
Nutter, Robert L.
Belmont
Chambers, Jack A.
Berkeley
Birge, Raymond T.
Brode, Robert B.
Edwards, Hiram W.
Gordon, George M.
Jenkins, F. A.
Marg, Elwin
Minor, Ralph S.
Stoddard, K. B.
White, H. E.
Beverly Hills
Bednarz, Felix
Ceccarini, Olindo O.
Greenspoon, R.
Burbank
Love, Bernard
China Lake
Anthony, Romuald,
DeBell, Arthur G.
Dember, Alexis B.
Estey, Roger S.
Herman, R. W.
Martz, E. P., Jr.
Nichols, Lawrence
Tobin, Bernard
Culver City
Berlant, Emmanuel
Downey
Davenport, Lawrence J.
Gillis, Ronald C.
East Whittier
Horsfall, R. Bruce, Jr.
El Cerrito
Conway, John G.
Eastmond, E. John
Encino
Clothier, Robert F.
Garvey
Brown, Daniel D.
Glendale
Hasler, Maurice F.
Proctor, Don R.
Vaile, C. A.
Glendora
Kennard, Theodore
Hollywood
Conant, Russell W.
Dearing, L. M.
Harrison, William H.
Huse, Emery
Kelley, William F.
Mellor, Lewis L.
Stafford, Jerome W.
Inyokern
Wallin, Walter
Whitney, T. R.
Long Beach
Doane, Edwin A.
Elmstrom, George P.
Fleischman, William E.
Wentworth, Hazel A.
Los Altos
Schepler, Herman C.
Los Angeles
Ball, J. A.
Crescitelli, F.
Dauber, Joseph
Davis, Faurest
Dodd, L. E.
Drescher, Bernard C.
Gitson, Leonard J.
Herron, James H.
Hofstetter, Henry W.
Hoggan, Lee W.
Holmes, John R.
Jahn, Theodore L.
Kaplan, Joseph
Klein, Arthur L.
Knoll, Henry A.
Nusbaum, Ralph E.
Stimson, Russell L.
Taylor, Philip H.
Manhattan Beach
Suffield, Frederick G.
Mt. View
Frels, Robert H.
Orinda
Baker, James G.
Palo Alto
Leighton, Philip A.
Pasadena
Anderson, J. A.
Cady, Willoughby M.
Dwyer, Robert J.
Graham, Robert C.
Hirsh, F. R., Jr.
King, Arthur S.
King, Robert B.
Miller, William C.
Millikan, R. A.
Pettit, Edison
Simmons, Edward E., Jr.
Thorburn, Eugene K.
Van Lear, George A., Jr.
Williams, W. Ewart
Wulf, Oliver R.
Pico
Roos, Paul A.
Pittsburg
Zimmerly, Ray A.
Placerville
Sharman, Hynton I.
Redlands
Marsh, H. E.
Redwood City
Foster, Charles P., Jr.
Richmond
Harrigan, Robert F.
Morgan, Meredith W., Jr.
Ross
Brice, Arthur T.
San Diego
Cotton, C. F.
Kerr, C. H.
McRae, Daniel B.
Selby, Horace H.
Wiedow, Carl P.
San Francisco
Barkley, Charles G.
Behner, H. C.
Garin, P. V.
Mathers, Marc G.
Mortimer, Forrest S.
Newell, Robert R.
Parsons, Alfred H.
Rood, Joseph L.
Strait, Louis A.
Swett, Hubert C.
Santa Barbara
Loutfallah, Michel
Miller, Charles G.
Santa Monica
Leighton, Thomas C.
Sonett, Charles P.
South Pasadena
Clark, John W.
National Technical Laboratories
West Los Angeles
Hansen, Waldemar G.
Kallmann, Hilde K.
Whittier
Bender, David F.
Pickering, P. W.

COLORADO—10

Aurora
Potter, William J., Jr.
Boulder
Blair, Julian M.
Lubovich, Vladimir P.
Schnable, George K.
Todd, Edward P.
Denver
Pollard, Glenn E.
Fort Collins
Weber, Louis R.
Georgetown
Reese, Herbert M.
Golden
Carpenter, Clark B.
Phelps, Robert T.

CONNECTICUT—63

Bridgeport
Linsley, Seymour G.
Malloy, James E.
Darien
White, John U.
Fairfield
Warren, Winthrop D.

Forestville
Hotchkiss, Robert N.
Glenbrook
McCarthy, Edward Lloyd
Perkin, Richard S.
Perkin-Elmer Corporation
Williams, Van Zandt
Greenwich
Anderson, Wilmer C.
Haskell, William P.
Torley, Robert E.
Hartford
Devol, Lee
Roberts, Sidney H.
Manchester
Pond, Samuel E.
Meriden
Uhler, Horace S.
New Canaan
Loomis, F. Kimball
New Haven
Cooksey, C. D.
Day, Herbert W.
Eaton, William W.
Engelder, Theodore Carl
Miles, Walter R.
Milligan, William E.
Watson, William W.
Wiedmann, M. L.
New London
Dimmick, Forrest L.
Farnsworth, Dean
Sperling, H. G.
Noroton
Hudson, Richard D.
Norwalk
Gray, G. Francis
Walton, Sam F., Jr.
Plainville
Schwartz, Morris
Putnam
Burton, Allan L., Jr.
Rowe, Louis F.
Ridgefield
Fraser, Walter A.
Rockville
Perry, Edward C., Jr.
Shelton
Taylor, Harold H.
Springdale
Jordan, Joseph, Jr.
Stamford
Bennett, Alva H.
Brown, Morden G.
Burton, Charles J.
Collyer, P. Wardham
Cunningham, F. W.
Hall, Vincent C.
Hirt, Robert C.
Jupnick, Helen
Kavanagh, Arthur J.
Lambert, William E.
Osterberg, Harold
Robins, R. S.
Stamm, Robert F.
Weltz, Hildegard
Storrs
Timoshenko, G. S.
Walker, M. J.
Waring, Charles E.
Suffield
Clarke, Richard G.
Thompsonville
Seass, Stewart
Waterbury
Barry, F. M.
Leichtle, Paul A.
Palmer, Earl W.
West Hartford
Fuehring, Christina
Park, Robert H.
Windsor Locks
Ford, Clinton B.

DELAWARE—16

Newport
Lyon, Donald W.
Wilmington
Aughey, Henry
Baum, Frederick J., Jr.
Bryant, W. M. D.
Conner, Willard P.
Downing, Joseph R.
Dunlop, E. C.
E. I. du Pont de Nemours and Company, Inc.
Friel, Daniel D.
Glasser, Leo G.
Kenney, Arthur W.
Kenyon, Wescott C.
Meloon, D. T.
Osborn, Robert Henry
Smith, Paul E., Jr.
Troy, Daniel J., Jr.

DISTRICT OF COLUMBIA—96

Washington
Abbot, Charles G.
Acquista, Nicolo
Aldrich, L. B.
Angier, James F.
Arnold, George W., Jr.
Aronson, C. J.
Ballinger, John C.
Barbrow, L. E.
Bastron, Harry
Bates, Frederick J.
Beck, Carl A.
Benson, Nels C.
Bozman, William R.
Breckenridge, F. Chapin
Brode, Wallace R.
Brown, Robert H.
Burstein, Elias
Coblentz, W. W.
Condon, Edward U.
Corliss, Charles H.
Corning, Mary E.
Crittenden, E. C.
Curcio, Joseph
Darby, Hugh H.
Davis, Raymond
Dawson, Leo H.
Dorsey, Herbert G.
Dunkelman, Lawrence
Emerson, Walter B.
Forman, Nyna L.
Furlong, L. R.
Gibbs, R. Clifton
Gibson, K. S.
Grabau, Martin
Hammond, H. K., III
Harvey, Marion M.
Haupt, Geraldine W.
Heilprin, Laurence B.
Howerton, Hugh K.
Hubbard, Donald
Hulburt, Edward O.
Humphreys, C. J.
Insley, Herbert
Jones, Ernest J.
Judd, Deane B.
Judson, Lewis V.
Keegan, Harry J.
Kelly, Kenneth L.
Kessler, Karl G.
Keuper, Jerome P.
Kiess, C. C.
Koomen, Martin
Kruegel, Shea LaBonte
Krumrine, Elizabeth M.
Lamb, Mary A.
Liddel, Urner
Lock, Charles
Lovell, Donald J.
Lovoff, Adolph
Meggers, William F.
Mohler, F. L.
Murata, Kiguma J.
Nickerson, Dorothy
Nimeroff, Isadore
Nutting, P. G., Jr.
O'Bryan, Henry Miles
Peters, C. G.
Phelps, F. P.
Plyler, E. K.
Projector, Theodore
Purcell, James DeWitt
Radford, Lawrence
Ryan, Lloyd F.
Sanderson, John A.
Saunders, James B.
Scribner, Bourdon F.
Sitterly, Charlotte M.
Smith, Newbern
Snavely, Benjamin L.
Stair, Ralph
Stephens, Robert E.
Stich, Jules N.
Stimson, H. F.
Talbott, F. Leo
Teele, Ray P.
Tilton, Leroy W.
Tousey, Richard
Tuckerman, L. B.
Vance, C. F.
Watanabe, Kenichi
Wensel, H. T.
Westfall, Oliver
Whitmore, William F.
Winger, Edward H.
Woodside, C. S.
Wright, Fred E.

FLORIDA—3

Dayton Beach
Stickney, George H.
Pensacola
Niven, Jorma I.
Sarasota
Freeman, Ellis

GEORGIA—7

Atlanta
Chason, A. L.
Goodman, Thomas P.
Woolner, Edward S., Jr.
Decatur
Blumer, James W.
Thaxton, Karl L.
Dry Branch
Lyons, Sanford C.
Rossville
Simon, Frederick T.

IDAHO—1

Kellogg
Bethune, Angus Y.

ILLINOIS—90

Aurora
Stumm, J. J.
Brookfield
Sansonetti, S. John

Champaign
Anderson, Scott
Drumheller, Carl E.
Smith, Buford, Jr.
Chicago
Amdursky, Mark Ernest
Austrian, L. A.
Barthel, C. E., Jr.
Beilman, Clarence
Bell & Howell Company
Betz, Howard
Brody, James K.
Bruno, Michael H.
Budde, E. F.
Countryman, M. Alden
Donnelley, R. R., & Sons Company
Drucker, Albert
Fred, Mark S.
Gaertner Scientific Corporation
Gates, Peter Satterlee
Goldblatt, Alan
Goleb, Joseph A.
Granville, Walter C.
Herrmann, Leon C.
Ireland, R. Paul
Kasha, Michael
Keller, F. D.
Klapperich, Alfred J.
Kluver, Heinrich
Krauss, Walter
Lewis, Robert E.
Marron, T. U.
Marslek, Emil J.
Miles, John R.
Minkler, Marcus W.
Monk, George S.
Nachtrieb, Norman H.
Nowicki, Edward R.
Roberts, Richard G.
Rusch, Mildred Lee
Schulz, LeRoy
Simpson Optical Mfg. Co.
Slagel, Milton E.
States, M. N.
Strickland, W. P., Jr.
Sullivan, H. M.
Swain, Asa W.
Szegho, C. S.
Tomkins, F. S.
Townsley, M. G.
Urbain, Walter M.
Youngkrantz, Howard R.
Zieler, Hans Wolfgang
Chicago Heights
Mitteldorf, A. J.
Schultz, Harvey A.
Des Plaines
Benson, B. S., Jr.
East St. Louis
Gitzen, W. H.
Utley, Don
Evanston
Cashman, Robert J.
Crew, Henry
Ewald, Arno W.
Fisher, R. A.
Frerichs, Rudolf
Huxford, Walter S.
Klopsteg, Paul E.
Peck, Edson R.
Spence, B. J.
Lake Bluff
Foote, Paul C.
Lake Forest
Smith, Albert M.
Lake Villa
Halverson, Gilbert
Lincolnwood
Woodson, Robert A.
Monsanto
Sharp, J. W.
Naperville
Yoder, Elwin C.
Oak Park
Smith, Warren J.
Staunton, John J.
Switzer, M. H.
Peoria
Melvin, E. H.
Richardson, K. T.
Urbana
Cohen, Jozef
Englis, Duane T.
Hart, Alvin L.
Horn, H. W.
Kraehenbuehl, J. O.
Loomis, F. W.
Miller, Wendell E.
Seitz, Frederick
Waukegan
Prest, J. Irving
Westchester
Elarde, P. F.
Wilmette
Gilmour, C. Allan
Wood River
Jones, Llewellyn C., Jr.

INDIANA—19

Bloomington
Leininger, R. K.
Verplanck, William S.
Fort Wayne
Essig, Sanford F.
Hine, Sheldon H.
Hammond
Yaseen, George
Indianapolis
Calkins, Tracy H., Jr.
Duckwall, Frank E.
Hatfield, William N.
Noyes, Bradford
Lafayette
DeVries, Thomas
Kline, John V.
Meissner, Karl W.
Mellon, M. G.
Marion
Lattimer, Charles T.
Terre Haute
Howlett, B. A.
West Lafayette
Menke, Warren W.
Whiting
Graves, Donald B.
Porsche, Francis W.
Winchester
Stump, Herman K.

IOWA—11

Ames
Carr, Percy H.
Earls, Lester T.
Fassel, Velmer A.
Kehres, Paul W.
Kunerth, William
Palubinskas, Felix S.
Sinsheimer, Robert L.
Woodrow, Jay W.
Iowa City
Stewart, George W.
Tyndall, E. P. T.
Sioux City
Gwinn, Ira J.

KANSAS—1

Hays
Zinszer, Harvey A.

KENTUCKY—4

Beuchel
Nisbet, D. F.
Fort Knox
Clark, Melvin D.
Louisville
Braden, William E.
Goodman, James S.

LOUISIANA—3

Baton Rouge
Tenney, Horace M.
New Orleans
O'Connor, Robert T.
Schales, Otto

MAINE—5

Eliot
Shook, G. A.
Orono
Bennett, Clarence E.
Crofutt, Charles B.
Waterville
Brown, Sherwood
Swans Island
Mohler, Nora May

MARYLAND—76

Baltimore
Andrews, Donald H.
Baker, Howard D.
Barton, Vola P.
Beidler, Lloyd M.
Bellamy, Blanche R.
Benesch, William M.
Bronk, Detlev W.
Chapanis, Alphonse
Crosswhite, Henry M., Jr.
Davis, William Chester
Dieke, G. H.
Friedenwald, J. S.
Hartline, H. Keffer
Lentz, Charles H.
McCubbin, T. King, Jr.
Macht, David I.
Mooney, C. Frank
Reimann, Genevieve
Richards, J. Dudley
Rowland, William M.
Scholz, Louis A.
Sloan, Louise L.
Stark, Robert Martin
Strong, John
Talbot, Samuel A.
Travis, James R.
Webb, Carl E.
Wood, R. W.
Bethesda
Brackett, Frederick S.
Draeger, R. H.

Gould, Wendell O.
Jacobs, Donald H.
Washer, Francis E.

Chevy Chase
Balcom, Margaret M.
Douglas, Charles A.
Gardner, Irvine C.
Kennard, Ralph B.
Maxwell, Louis R.
Smith, Francis A.

College Park
Morgan, Raymond

Ednor
Mahan, A. I.

Gaithersburg
Helz, Armin W.

Havre de Grace
Lipton, Sidney M.

Highland
Carl, Howard F.

Hyattsville
Armstrong, David W.
Davis, Russell E.
Myers, Alfred T.
Peterson, Maurice J.
Saylor, Charles P.
Young, Theodore R.

Kensington
Creitz, E. Carroll
Gayhart, E. L.

Lanham
Scofield, Francis

La Plata
Johnson, Lyle T.

Laurel
Dorsey, N. Ernest

Mt. Ranier
Stern, Joshua

Rockville
Ball, Joseph J.

Silver Spring
Byers, R. C.
Feder, Donald P.
Goldberg, Benjamin
Liben, William
Lovins, Gerald H.
Lowe, Donald S.
McElroy, Olive E.
Mundie, Lloyd G.
Ramsay, B. P.
Schroeder, Jacob
Silverman, Shirleigh
Swanson, Mark
Tiedeman, John A.
Unger, Hilbert J.
Wilkie, John B.

Takoma Park
Templin, Herman A.

Towson
Perry, Wilbur H.

West Hyattsville
Slavin, Walter

Westminster
Summers, R. D.

MASSACHUSETTS—153

Amherst
Soller, Theodore
Stifler, W. W.

Arlington
Lanza, Carmelo
Spencer, Roy C.

Auburndale
Ryan, Charles E.

Bedford
Harrison, Jamison R.

Belmont
McFee, Raymond H.

Beverly
Gibb, Thomas R. P.

Boston
Britton, William C.
Burian, Hermann M.
Culver, William H.
Cook, Ellsworth B.
Eikrem, Lynwood O.
Gould, Lawrence
Greenwood, Willard P.
McFarland, Ross A.
Macdonald, Duncan E.
Rines, David
Smith, William
Welch, George B.

Brookline
Champeny, J. C.
Cohen, Joseph H.
Ehrenfried, George
Vigo, Samuel

Cambridge
Baird, Walter S.
Beaman, Elizabeth O.
Billings, B. H.
Blout, Elkan R.
Carpenter, Robert O'B.
Chapman, Robert M.
Compton, K. T.
Dudley, Beverly
Duntley, Seibert Q.
Eastham, Melville
Eaton, S. Edward, Jr.
Federer, Charles A., Jr.
Finch, Rogers B.
Forbes, Alexander
Furnas, Thomas C., Jr.
Gallipeau, Robert B.
Hardy, Arthur C.
Harrison, George R.
Harvey, G. G.
Haskell, Stanley W.
Hoffman, R. J.
Jones, R. Clark
Kolm, Henry H.
Land, Edwin H.
Loofbourow, John R.
Lord, R. C.
Lyman, Theodore
Mager, Louis
Matz, Charles H.
Moon, Parry
Morse, Richard S.
Mueller, Hans
Nottingham, Wayne B.
Oldenberg, Otto
Oliver, Norman J.
Perkins, Willis D.
Petersen, Max
Polaroid Corporation
Pope, Arthur
Power, John W.
Power, John W., Jr.
Pulling, Nathan H.
Robinson, David Z.
Rosenblum, Louis
Rule, John T.
Schwarz, Edward R.
Sears, Francis W.
Shurcliff, William A.
Sterner, John
Stockbarger, D. C.
Wald, George
Walters, S. H.
Whitney, Charles A.
Wrigley, Walter
Young, F. Mansfield

Chestnut Hill
Devlin, James J.

Concord
McPherson, Paul M.
Parke, Nathan G., III

Dedham
McNally, Frederick A.

Dodge
Gunter, Roy Chalmers, Jr.

Dorchester
Tytell, Boris H.

Duxbury
Bittinger, Charles

Everett
Kelly, Joseph B.

Greenfield
Wing, Howard E.

Ipswich
Norman, Daniel
Wylie, Robert R.

Lawrence
O'Neil, Frank J.

Lenox
Ashley, Samuel E.

Lexington
Burke, Bernard F.
Jurmain, Jacob H.
Schneider, Edwin G.
Williamson, Donald E.

Lincoln
Mann, David W.

Malden
Anderson, James C.
Frost, Eugene N.
Osgood, G. Robert, Jr.

Mattapan
Hargreaves, Walter A.

Medford
Ballard, Stanley S.
Smith, Charles G.
Terrio, F. J.

Milton
Hickey, Albert E., Jr.
Sutton, Adelaide

Needham
Stark, Stephen W.
Stetson, Harlan T.

Needham Heights
Bentley, Edward P.

Newton
Merrill, Dwight P.

Newton Centre
Amann, Rudolf
Fentin, Arthur

Newtonville
Law, William S.

Northampton
Anslow, Gladys A.

North Brookfield
Cooke, Frank

North Grafton
Fipphen, John S.
Morris, Charles A.

Norwood
Watson, John T.

Randolph
Reed, Allan W.

Rockland
Wheeler, Burton W., Jr.

Salem
Brynes, Kermit
Butler, Keith H.
Levesque, Henry J.
Quinn, John E.

Southbridge
American Optical Company
Barnes, R. Bowling
Boeder, Paul
Davis, John K.
Glancy, Ann E.
Haynes, Paul H.
Tillyer, E. D.
Wells, John M.
Whitney, Donald B.

South Hadley
Allen, Mildred
Carr, Emma P.

Springfield
Ingle, George W.

Sturbridge
Herman, William F.

Waban
Jarrell, Richard F.

Waltham
Hayward, Robert M.

Wellesley
McDowell, Louise S.
Miley, H. A.
Weeks, Dorothy
Zigler, Michael J.

Wellesley Hills
Hyde, Walter L.

West Lynn
Stimson, Allen

Weston
Grey, David S.

West Springfield
Walrath, E. K.

Woburn
Mackay, Ernest

Woods Hole
Klebba, Arthur A.

Worcester
Burns, William F.
Lucas, Ernest H.
Parker, Allan E.
Sheftel, Milton S.

MICHIGAN—65

Ann Arbor
Argus, Inc.
Blackwell, H. Richard
Boettner, Edward A.
Boyd, Robert A.
Enns, J. H.
Harvey, James E.
Kessler, Heini B.
Kincaid, W. M.
Kraus, Edward H.
Meyer, Charles F.
Peters, C. W.
Randall, H. M.
Sawyer, Ralph A.
Sinnett, Vivian L.
Sleator, William W.
Tanner, Wilson P., Jr.
Taylor, John Hall
Williams, Robley C.
Wolfe, Ralph A.

Berkley
Fry, David L.

Dearborn
Bryan, Ford R.
Tuttle, Henry A.

Detroit
Boltz, David F.
Boyd, Bernard R.
Canning, Robert A.
Chamberlain, Katherine
Dietert, Harry W.
Edgar, William J.
Fuhremeister, John C.
Gordon, Arnold H.
Lamb, Frances W.
Mager, Robert G.
Mueller, Alexander
Poetker, Albert H.
Rassweiler, Gerald M.
Schuch, John
Vergho, Joseph C.

East Lansing
Bartley, S. Howard
Ewing, Dwight T.
Noble, Robert H.
Ogle, H. V.

Farmington
Nahstoll, George A., Jr.

Ferndale
Brandt, Stanley M.

Flint
Keehner, John B.

Kalamazoo
McGonnagle, Warren J.
Rood, Paul

Midland
Barstow, Ormond
Graham, Joseph P.
Grossman, Harold H.
Herscher, L. W.
Hess, T. M.
Peterson, R. E.
Reinhardt, Lyle G.
Saunderson, Jason L.
Ullrey, Mark A.
Wright, Norman

Muskegon
Gruszecki, Peter J.
Sampson, A. M.

Muskegon Heights
Hesling, Francis M.

Pontiac
McMath, Robert R.
Racine, F. L.

Royal Oak
O'Neill, W. R.

Willow Run
Neill, Howard W.

Wyandotte
Beyer, Karl W.
Kuentzel, Lester E.

MINNESOTA—15

Minneapolis
Anderson, Albert L.
Braden, John
Buchta, J. W.
Crawford, Bryce L., Jr.
Kliever, Waldo H.
Meehan, E. J.
Price, George R.
Schwartz, Samuel
Stenstrom, Wilhelm
Valasek, J.

Northfield
Fossom, Peter E.

Rochester
Ogle, Kenneth N.
Sheard, Charles

St. Paul
Rubens, Sidney M.

Wayzata
Brueske, George A.

MISSISSIPPI—1

State College
Wiseman, Robert S.

MISSOURI—15

Columbia
Pickett, Edward E.
Smith, Eastman

Ferguson
Field, Byron D.

Joplin
Whitford, Paul

Kansas City
Burns, Loren V.
Trimble, Frank H.
Ziegler, George E.

Rolla
Cleveland, E. Lynn

St. Louis
Bubb, Frank W.
Merle, John, Jr.
Skeffington, Mary Jane

Sappington
Cobb, Percy W.

University City
Meyer, H. Sigmund

Webster Groves
Munch, Ralph H.
Stansbrey, John J.

MONTANA—1

Helena
Holter, Norman J.

NEBRASKA—4

Lincoln
Jensen, J. C.

Omaha
Hayden, Charles K.
Oldham, Max S.
Spieth, Howard H.

NEW HAMPSHIRE—12

Durham
Clark, David G.
Daggett, Albert Frederick
Howes, Horace L.

Hanover
Ames, Adelbert, Jr.
Bannon, Robert E.
Campbell, C. J.
Dimitroff, George Z.
Gliddon, Gordon H.
Karwoski, Theodore F.
Meservey, Arthur B.
Proctor, Charles A.
Triller, Wendell

NEW JERSEY—121

Arlington
French, A. H.

Asbury Park
Shillaber, Charles P.

Barrington
Edmund Salvage Company

Basking Ridge
Hartmann, Werner

Belvidere
Hemmendinger, Henry

Bergenfield
Brown, Earle B.

Bloomfield
Beggs, Eugene W.
Eichner, L. C.
Williams, David L.

Bound Brook
Buc, George L.
Chalupski, Victor
Kaselis, Ruth Abbott
Royer, George L.
Stearns, Edwin I.

Caldwell
Rugg, Frank M.
Rudolph, Hellmuth C.

Camden
Maloff, Ioury G.

Carteret
Ernst, Runyon G.

East Orange
Aster, Alvin K.
Hillman, Conway D.

Eatontown
Blutman, E.
Marcus, Bernard

Elizabeth
Bell, Mary F.
Weinhart, Howard W.

Englewood
Berger, Curt E.
Wood, Francis C.

Fair Lawn
Campbell, H. N.
Clutz, Claude S.
Garland, Daniel L.

Fanwood
Olsen, Robert M.

Fort Monmouth
Keck, P. H.
Leistner, Karl

Glen Rock
Van Dien, J. Edward

Grasselli
Brady, Lynn J.

Hackensack
Siganowick, John

Haddonfield
Sachtleben, Lawrence T.

Harrison
Guettel, Charles L.
Power, Archie D.

Hawthorne
Saltzmann, Max

Hoboken
Hawkes, John B.
Keuffel & Esser Company
Keuffel, Carl W.
Jersey City
Blackham, Wilfrid
Kearny
Austin, J. B.
Leonia
Farwell, H. W.
Little Silver
Green, Milton
Lee, Bernard S.
Long Branch
Field, Norman J.
Kaprelian, Edward K.
Merrill, H. J.
Manville
Miller, M. C.
Maplewood
Hazeltine, Alan
Schweizer, Ernest
Swindells, Frank E.
Merchantville
Patterson, J. Edward
Metuchen
Noebels, Henry J.
Price, E. E.
Millington
Goodwin, William J.
Murray Hill
Gnorich, W.
Herriott, William
Jaycox, Edwin K.
Kingsbury, Edwin F.
Molnar, Julius P.
Reynolds, Frederick W
Newark
Anderson, William T., Jr.
Balamuth, Lewis
Bleiweiss, Arthur F.
Killian, D. B.
Lincoln, Arnold J.
Ranger, R. H.
New Brunswick
Coy, Nettie H.
Mullin, Harold R.
Reed, J. D.
Newton
Lighty, Paul E.
Potter, Rowland S.
Nutley
Howland, Walter A.
Parlin
Conklin, O. E.
Passaic
Gibbons, Willis A.
Hampton, Robert R.
Lampman, Moreon E.
Wilber, David T.
Perth Amboy
McLellan, Roy D.
Plainfield
Lord, Bradley
North, Charles H.
Smith, Richard P.
Stilwell, G. Raymond
Princeton
Alford, W. P.
Bube, Richard H.
Chase, Aurin M.
Davidson, Ward F., Jr.
Epstein, David W.
Foss, Carl E.
Furman, N. Howell
Leverenz, Humboldt W.
Pehtâ, Arnold John
Shenstone, Allen G.
Sziklai, George C.
Rahway
Farnsworth, Marie
Loofbourow, Rodger W.
Red Bank
Bluford, Benjamin L., Jr.
Ridgefield
Geier, George
Ridgewood
Hill, Lyman P.
Moffitt, G. W.
Riverton
Younkin, S. G.
Short Hills
Davisson, C. J.
South Amboy
Jacobsen, Arthur E.
South River
White, Deane R.
Summit
Farr, Wanda K.
Wheat, J. Allen
Upper Montclair
Arnott, E. G. F.
Ives, Herbert E.
Webber, Alfred C.
Verona
Wyckoff, Norman W.
Watchung
Woods, John T.
West Englewood
Walton, John F.
Westfield
Gray, Arthur W.
Read, Harry S.
Wiley, S. Richard
West Orange
Edison, Theodore M.
Westwood
McWilliam, Leslie H.
Woodbury
Hochgesang, Frank P.

NEW MEXICO—11

Alamogordo
Williamson, Harold G.
Albuquerque
Jean, J. N.
Keller, John S.
Lohse, John M.
Martin, Guy V.
Los Alamos
Holland, Thomas E.
Lipinski, Albert J.
Marling, John B.
Sabine, George B.
Simi, Oliver R.
Santa Fe
Porter, Eliot F.
Socorro
Harris, Clyde W.

NEW YORK—487

Albany
Crowe, M. O'L.
Rankin, Charles W.
Waldbauer, Louis J.
Walker, Amy
Amsterdam
Hanlon, John J.
Athens
Hallock, Herbert B.
Baldwin
Robinson, William J., Jr.
Bayside
Oszy, Alexander J.
Vogel, Roderick Quentin
Beacon
Cummings, C. E.
Beechhurst
Marks, Alvin M.
Binghamton
Arnold, Paul
Bingham, Ronald H.
Current, Ira B.
Harsh, Harold C.
Hoerlin, Hermann
Knop, Victor R.
Larson, Ernest T.
Lenz, Lester R.
Misener, Garland C.
Morreall, H. W., Jr.
Reese, Warren B.
Sweet, Monroe Hamilton
Bronx
Doller, Samuel
Dollmann, Elsie M.
Feldman, Sidney
Gilstein, Jacob B.
Hett, John H.
Schafstein, Nathan J.
Bronxville
Greene, Bernard F.
Nolan, Philip
Brooklyn
Barbera, Robert A.
Bavley, A.
Bergere, Leonard M.
Bergman, Lester V.
Bernstein, Harry S.
Breitman, Seymour
Cahill, John J., Jr.
Cohen, Irving E.
Davis, George W. C.
Davis, George E.
Day, George
Dunn, E. J., Jr.
Engelson, Howard R.
Friedman, Harry S.
Harris, L.
Helson, Harry
Hughes, Harold K.
Isaacson, Leon D.
Johnston, Elizabeth
Kaplowitz, Morris
Lawson, W. L.
Maerz, A.
Means, J. A.
Parke, Harry G.
Rosenberg, Ben
Schwarzschild, Myron
Stevens, E.
Stone, Florence M.
Buchanan
Wurzburg, F. L., Jr.
Buffalo
Cohen, Ernest
Ford, James W.
French, Hobert W., Jr.
Fuhr, Allen B.
Gustin, A. F.
Jones, Donald C.
Kloepfer, Barbara R.
LeRoy, V. M.
Magill, Lincoln C.
Meyer, Edgar J.
Mrozowski, Stanislaw
Muller, Robert M.
National Aniline Division, Allied Chemical & Dye Corporation
Peck, William F.
Ripley, D. L.
Signeur, Austin V.
Small, John H.
Wilkins, J. Ernest, Jr.
Zimmerman, Carlton F.
Canton
Smith, John F.
Conklin
Hugos, Henry J., Mrs.
Corning
Bacon, James F.
Cartwright, C. Hawley
Corning Glass Works
Dalton, Charles C.
Dorman, William H.
Gage, H. Phelps
Lillie, Howard R.
Littleton, Jesse T. Jr.
Parker, Charles J.
Sheldon, John L.
Smith, Gail P.
Werner, Alan J.
Wetmore, Warren L.
East Rochester
Lueck, Irving B.
O'Brien, Brian
Eggertsville
Brandstetter, F. X.
Martin, Marcel A.
Elmhurst
Braun, Ben
Kollsman Instrument Division, Square D Company
Elmira
Stong, Guy E.
Endicott
Malmros, Alf

Fairport
Carlson, Chester F.
Colton, Howard C.
Friar, Lawrence B.
Flushing
Brophy, Vincent A.
Pearson, Frank A.
Raitiere, Louis
Tralli, Nunzio
Forest Hills
Bechtold, Edwin W.
Lowen, Herbert
Rosett, Bernard
Fulton
Ferrari, C. G.
Garden City
Bronson, S. Davis
Spike, J. Edward, Jr.
Geneva
Bartlett, Neil R.
Haussmann, Alfred C.
Spengler, John A.
Glen Cove
Winnek, Douglas Fredwill
Hamilton
Gleason, Paul R.
Hempstead
Faurote, Richard B.
Holley
Klemm, Robert E.
Honeoye
Sundeen, Earl I.
Huntington Station
Babish, Richard
Brown, Fordyce M.
Tuttle, Clifton M,
Irvington
Schaffers, T. W. M.
Duffendack, O. S.
Ithaca
Cottrell, Casper L.
Fogelsanger, Aldus
Gartlein, Carl Witz
Grantham, G. E.
Murdock, Carleton C.
Shaw, R. William
Jackson Heights
Monahan, Thomas I.
Jamaica
Carter, Jefferson A.
Fairchild Camera & Instrument Corporation
Tocher, Ralph B.
Jamaica Estates
Been, Robert B.
Johnson City
Ketcham, Henry C.
Kenmore
Blaisdell, B. E.
Gillette, R. H.
Marston, Alfred L.
Lackawanna
Jackson, Trumbull S.
Lockport
Magrun, William H., Jr.
Windle, Maurice L.
Long Island City
Ainsworth, George
Banet, Leo
Ellis, S. B.
Hellige, Peter W.
Schaffner, F. Q.
Sherman, Bennett
Lowville
Fenning, Leonard Michael
Lynbrook
Dixon, Leslie G.
Malverne
Winter, Martin H.
Manhasset
Bitner, Ralph E.
Carbonara, Victor E.
Eckweiler, Howard
Mineola
Rattray, George
Mt. Kisco
Blake, Edwin M.
Fisher, Harold M.
Mt. Vernon
Abel, Irving R.
Hineline, Harris D.
Wetzel, Reinhard A.
Newburgh
Macbeth, Norman
New Hyde Park
Heitzmann, Janet Fuller
Leftwich, Richard F.
New Rochelle
Ross, E. R.
Ullom, James R.
New York
American Cystoscope Makers, Inc.
Back, F. G.
Barton, Henry A.
Bastien, Roy C.
Bell, R. H.
Bell Telephone Laboratories, Inc.
Beller, William C.
Berens, Conrad
Besner, Aaron
Bing, Joseph M.
Birren, Faber
Bragg, H. E.
Brooke, Richard Thomas
Carlsen, Conrad P.
Chace, Robert R.
Chikofsky, S.
Coleman, Eugene F.
Cox, Maurice E.
Crouch, C. L.
Davis, Bergen
Derksen, Willard L.
Dolton, Dorothy
Draves, Carl Z.
Dunn, Gano
Failla, G.
Farrand Optical Company, Inc.
Ferguson, W. F. C.
Finkelstein, Isidore S.
Fish-Schurman Corporation
Fread, Bernard
Gardner, William A.
Goldmark, P. C.
Goldsmith, Alfred N.
Graham, C. H.
Greenleaf, Allen R.
Grimson, Samuel B.
Grinoch, Paul
Grosch, H. R. J.
Hardy, J. D.
Hardy, LeGrand H.
Hebo, Halfdan
Hillyer, Curtis
Holst, W. A.
Interchemical Corporation
Kashdan, William H.
Korbel, Harold
Krewer, Semyon E.
Lamar, Edward S.
Lerse, John J.
Leventhal, J. F.
Lit, Alfred
Little, William F.
Martin, Alfred E.
Matzka, Liselotie Heim
Maurer, John A.
Miller, Osborn M.
Munsell, A. E. O.
Murphy, Eugene F.
Muscat, Lewis
Nadir, Mark T.
Newcomer, H. Sidney
Pajes, Wolf S.
Paul, M. Rea
Pavelle, Leo
Pegram, George B.
Rand, Gertrude
Ratoosh, Philburn
Reilly, Frank J.
Rittler, M. C.
Rohrbaugh, John H.
Roots, Yale K.
Rosin, Seymour
Rothrock, Robert W.
Sacher, David
Schauer, Charles H.
Scheick, J. A.
Schmid, Fred
Schurman, Ferdinand
Smith, Daniel
Smolar, Murray M.
Speyer, Edward M.
Stein, Eugene
Thielens, Emil H.
Treleaven, Clifford
Tyler, John E.
Varden, Lloyd E.
Watson, John G.
Webb, Harold W.
Wertenbaker, Clark
Williams, Frederick D.
Williams, Horatio B.
Wolff, R. I.
Wormser, Eric M.
Niagara Falls
Curtis, J. Alfred
Foregeng, William D.
Porter, Galen
Norwich
Ells, Victor R.
Paul, Henry E.
Oceanside
Urbanik, John G.
Oneida
Iredale, John R.
Oneonta
Micco, L. A.
Painted Post
Gage, O. A.
Peekskill
Ednalite Optical Company, Inc.
Pittsford
Dakin, Ralph K.
Pleasantville
Berger, France B.
Garman, R. L.
Rentoumis, George M.
Point Pleasant
Perkins, Willard T.
Port Washington
Swede, Hillard B.
Rochester
Aklin, George H.
Alexander, C. H.
Altman, Fred E.
Altman, Richard M.
Anderson, James M.
Bancroft, George H.
Bausch & Lomb Optical Company
Bausch, Carl L.
Benford, James R.
Bennett, Harold F.
Bishop, Fred M.
Blackmer, L. L.
Bloem, Harold H.
Brockway, Ellsworth M.
Brown, W. R. J.
Burnham, Robert W.
Campbell, Charles J.
Carnahan, Walter H.
Carpenter, Vance J.
Carroll, Burt H.
Chambers, Gordon A.
Chesna, John
Clapper, F. R.
Clark, Janet H.
Condit, Harold R.
Cook, Alan A.
Craig, William M.
Crewdson, E.
Day, Carl A.
Debenham, Jack K.
Dessauer, John H.
Discher, Wendell V.
Duboc, Charles A.
Dunham, Theodore, Jr.
Eastman Kodak Company
Edgerton, Richard O.
Eisenhart, M. H.
Ellestad, Gerhard A.
Epstein, L. Ivan
Evans, Charles H.
Evans, John C.
Evans, Ralph Merrill
Finkelstein, Nisson A.
Flint, Edward F., Jr.
Fontaine, Emile
Forrest, John W.
Fortmiller, Louis J.
Foster, Leon V.
Fowler, Richard Crosman
Gilkeson, David C.
Goetz, William E.
Graeper, Walter W.
Gramm, Charles F.
Greppin, Ernest H.

Hanson, W. T., Jr.
Harper, David C.
Hayes, John D.
Herzberger, Max
Higgins, George C.
Hoadley, H. Orlo
Holmes, F. M. E.
Hone, F. J.
Hopkins, Robert Earl
Hudson, Lena M.
Hurvich, Leo M.
Hutchinson, Nancy
Ingalls, Arthur L.
Jameson, Dorothea
Jarvis, J. G.
Jelley, Edwin E.
Jobe, Frederick W.
Johnson, Gerald A.
Jones, L. A.
Kaplan, Burton
Kingslake, Rudolf
Kisner, Walter I.
Kottler, Friedrich
Kreidl, Norbert J.
Krolak, Leo J.
Kunz, Joseph
Kurtz, Henry F.
Kurtz, John C.
Last, J. T.
Leurgans, Paul
Levin, Aaron
Loveland, Roger P.
Lowry, Earl M.
MacAdam, David L.
MacNeille, Stephen M.
Magliozzi, Joseph
Marks, Jerold S.
McAlister, E. D.
McFarlane, John W.
McIntyre, Rae Wyland (Mrs.)
McLeod, John H.
Mees, C. E. K.
Merrill, B. Darby
Michelson, Reuben S.
Miller, Oran E.
Miller, Thomas H.
Milligan, Francis H.
Milne, Gordon G.
Modney, William (Mrs.)
Morey, D. R.
Morris, Robert H.
Morrison, Charles A.
Morrissey, James H.
Murray, Allen E.
Nail, Nelson R.
Nelson, C. N.
Newhall, Sidney M.
Newhouse, Herman
Nielsen, Waldo J.
Orser, W. Donald
Ott, Harry G.
Overhage, Carl F. J.
Parker, Donald J.
Perrin, Fred H.
Pestrecov, K.
Pickering, R. D.
Polster, Harry D.
Putnam, Thomas E.
Reid, Charles D.
Reiss, Max
Richardson, David
Richardson, Earle E.
Rippel, Charles W., Jr.
Russell, Marion E.
Sandvik, Otto
Schade, W. E.
Scharf, Philip T.
Schoen, Arthur L.
Schwarz, George
Scott, Murray R.
Seidenberg, Richard L.
Shean, J. W.
Siegmund, Walter
Smith, F. Dow
Smith, John H.
Snitchler, L. Clyde
Sorem, Allan L.
Sprentall, H. Robert
Staud, Cyril J.
Steadman, Luville T.
Steiner, Oscar
Stevens, B. Vincent
Stevens, Paul W.
Straat, Harold W.
Stultz, Keith F.
Swann, William F.
Tackaberry, R. B.
Tatian, Berge
Taylor, Edward J.
Taylor, Joseph F.
Temple, Russell A.
Tolle, Karl
Townsend, Charles V. R.
Trivelli, A. P. H.
Tupper, John L.
Turner, Arthur Francis
Urbach, Franz
Watson, James S., Jr.
Weaver, Karl S.
Webb, Julian H.
Wieder, Harold
Wightman, E. P.
Wilde, Frederick G.
Williams, Franklin C.
Wilsey, Rex B.
Wolfe, Robert N.
Wood, Donald L.
Woodruff, Robert W.
Wooters, Glenn C.

Rome
Griffith, Jane Dick
Schatz, Frederick V.

St. Bonaventure
Sullivan, Francis J.

Saratoga Springs
Strock, Lester W.

Schenectady
Barnes, Norman F.
Blodgett, Katharine B.
Dushman, Saul
General Electric Company
Hupman, George H.
Jacobson, Woodrow R.
Koller, Lewis R.
Michaelson, J. L.
Newell, Raymond, F. Jr.
Rice, Chester W.
Studer, Frank J.

Seneca Falls
Rychlewski, Thaddeus V.

Shenorock
Engel, W. H.

Snyder
Reardon, Joseph D.
Sharp, Howard M.

Staten Island
Lindemann, Howard C.

Suffern
Frachtman, Henry

Syracuse
Mader, William A.
Oplinger, George
Warntz, Adrian L.

Thompkinsville
Brock, Frederick W.

Troy
Carragan, G. Howard
Gurley, W. & L. E.

Upton
Slavin, Morris

Wellsville
Broadhead, D. T.

Westbury
Bridgman, C. S.

White Plains
Longwell, Frederick P.

Williamsville,
Woernley, D. L.

Woodside
Harjes, Frederick W.

Yonkers
Arthur, John M.
Flory, Louis Paul
Mersereau, E. P.

NORTH CAROLINA—5

Asheville
Nitchie, Charles C.

Charlotte
Palmer, Roy A.
Stoll, Marion R.

Durham
Sponer, Hertha

Enka
Jolliff, E. Corwith

OHIO—109

Akron
Householder, Fred F.
Woodford, D. E.

Barberton
Dress, Kenneth S.

Bedford
Emery, Frederic H.

Canton
Vance, E. R.

Cincinnati
Andrews, John T. R.
Balinkin, Isay A.
Coffin, Allen
Dreyer, John F.
Merchant, M. Eugene
Rosevear, F. B.
Sperti, George S.
Westermann, Fred E.

Cleveland
Adams, Elliot Q.
Barnes, B. T.
Bedell, Howard M.
Buchele, Donald R.
Buck, G. B., Jr.
Conrad, Anne L.
Ditchman, J. P.
Easley, M. A.
Erikson, G. L.
Guth, Sylvester K.
Harrington, Roger E.
Hodgman, Charles D.
Hoover, P. L.
Hutchisson, Elmer
Larson, Daniel A.
Luckiesh, Matthew
Martin, William H.
Meese, G. E.
Reuter, Frederick W., Jr.
Rozsa, J. T.
Shankland, R. S.
Smith, Richard E.
Steeb, E. S., Jr.
Taylor, A. Hadley

Cleveland Heights
Lundin, C. A. Robert

Columbus
Alpern, Mathew
Fry, Glenn A.
Greenhouse, Harold M.
Hendley, C. D.
Henry, William M.
Hesthal, C. E.
Hole, Winston L.
Howard, John Nelson
Leslie, Elmer H.
Nelson, Richard C.
Oetjen, Robert A.
Oughton, Charles D.
Renshaw, Samuel
Russell, Howard W.
Smith, Clara D.
Stone, Conrad A.
Zeeb, Lawrence E.

Dayton
Aneshansley, C. H.
Beardsley, Niel F.
Bombe, H. A.
Brocklehurst, R. E.
Burka, Samuel M.
Fink, George A.
Gard, Orin P.
Hart, George C.
Katz, Amrom H.
Kean, Lee
Koch, Wendell R.
Lapenas, Torp A.
Nagel, Max R.
Nierenberg, Richard N.
Steingiser, Samuel
Univis Lens Company
Woodford, Edward B.

East Cleveland
Forsythe, W. E.
Spencer, Charles D.
Thayer, Richard N.

Euclid
Howald, T. S.
Howes, Walton L.
Poritsky, Abraham
Fostoria
Lozier, W. Wallace
Zavesky, Robert J.
Marietta
Phillips, Thomas D.
Miamisburg
Olt, Richard G.
Radford, Richard D.
Timma, D. L.
Middletown
Woodruff, J. F.
Newark
Franck, Kurt
Rolph, Thomas W.
Waggoner, Jack H.
North Canton
Bixler, Milo E.
Oxford
Billhartz, William H.
Painesville
Wilson, Mabel F.
Parma
Kalischer, P. R.
Ravenna
Ballard, James W.
Terrace Park
Chapman, James M.
Toledo
Dunipace, Donald W.
Kiser, M. G.
Powell, H. Eugene
Sharp, Donald E.
Shuck, Lowell M.
Van Zee, Arthur F.
Vincent, Harvard B.
Urbana
Laufer, Maurice K.
Warren
Baxter, R. C., Jr.
Lab, Roy F.
Wooster
Sayre, J. D.
Worthington
Ullrich, O. A., Jr.
Yellow Springs
Knorr, Harry V.
Robinson, True W.
Youngstown
Ross, Nicholas V., Jr.

OKLAHOMA—13

Bartlesville
Fast, Edwin
Rall, Harry T.
Thornton, Vernon
Wheeler, Gilbert V.
Enid
Allbright, Burnard D.
Armstrong, Gertrude
Dalrymple, George F.
Mitchell, Donald Emerson
Schulte, Daniel
Norman
Charles, George W.
Mikkelsen, Louis
Nielsen, J. Rud
Tulsa
Silverman, Daniel

OREGON—5

Corvallis
Garman, John C.
Weniger, W.
Eugene
Ellickson, Raymond T.
Portland
Parker, William L.
Sanford, Cecil E.

PENNSYLVANIA—142

Allentown
Waidelich, John A., Jr.
Bethlehem
Bayley, P. L.
Horscroft, W. F., Jr.
Irish, Paul R.
Serfass, Earl J.
Bryn Mawr
Michels, Walter C.
Vaux, George
Chadds Ford
Rossmassler, Selma
Creighton
Chess, James S.
French, Preston W.
Lytle, W. O.
Morris, Paul R.
Parker, Henry F.
Drexel Hill
Bell, Guy C., Jr.
Scott, William E.
Duquesne
Dunn, Edward J.
Easton
Beiswanger, John P. G.
Davidson, H. R.
Godlove, I. H.
Herrick, C. E., Jr.
McQuarrie, W. C.
Mitchell, Carl A.
O'Brien, Brian, Jr.
East Pittsburgh
Coles, Donald K.
Senko, Julia
Erie
DeWitt, W.
Grampian
Moore, William R.
Green Ridge
Henthorn, David W.
Harmarville
Russell, R. G.
Harrisburg
Wells, Franklin H.
Jeannette
Hatch, Edwin F.
Lafayette Hill
Bloomsburgh, Ralph A.
Lancaster
Brunner, Adolphus J.
Glover, Alan M.
Robinson, Howard A.
Widmyer, John H.
Latrobe
Heid, Roland
Narberth
Tabor, Lewis P.
New Kensington
Bishop, F. L., Jr.
Churchill, J. R.
Northampton
Cheesbrough, E. W.
Norwood
Rosenbaum, E. J.
Oakmont
Harmon, Duane D.
Palmerton
Barnett, Charles E.
DeVore, J. R.
Reimert, L. J.
Paoli
Chandler, Alfred B.
Philadelphia
Adler, Francis Heed
Applegate, Charles E.
Bamford, Henry S.
Blitzstein, William
Brice, Brooks A.
Coles, Harold W.
Cornog, I. Clyde
Crampton, George S.
Darby, C. Pfluger
Denton, Richard A.
Drabkin, David L.
Duncan, Ralph W.
Dyer, Clarence A.
Edelman, Norman B.
Geary, Paul A.
Gee, Alan E.
Gray, William T.
Haines, Jesse H.
Harrison, T. R.
Hill, George C., Jr.
Ilstad, Reidar
Jaggard, George
Kaspereit, Otto K.
Koenig, Bernard R.
Kraft, Frank Robert
Langley, Frank P., Jr.
Machler, Raymond C.
Monego, J. Constantin
Morse, Mark P., Jr.
Parsons, S. L.
Patrick, Francis B.
Peckham, R. H.
Pesce, Mario R.
Schaeffer, W. H.
Sherman, Jacob
Shreve, O. Davis
Spiegel-Adolf, Mona
Stevens, Ludlow
Theel, Percival
Thomas, Arthur H., Company
Witmer, Enos E.
Woodman, J. F.
Pittsburgh
Ashe, Frank C.
Brandt, Neill M.
Foote, Paul D.
Francis, C. B.
Friedel, Robert A.
Hodge, Edwin S.
Jones, Frank L.
Kruper, A. P.
Leberknight, C. E.
Lefkowitz, Martin
Maier, R. William
McKinley, Robert W.
Miller, Foil A.
Moreland, Ben A.
Oshry, Howard I.
Pellissier, G. E.
Pitzer, L. E.
Ruhe, Carl
St. Peter, Wilfred N.
Slish, Michael
Strasser, Alexander
Taylerson, Ewart S.
Tillotson, E. Ward
Unertl, John, Jr.
Venable, William M.
Warga, Mary E.
Webster, R. R.
Pottstown
Kepner, Harold P.
Reading
Dillon, Frank W.
Hettinger, Edwin L.
State College
Neuberger, Hans
Nitchie, Francis R., Jr.
Rank, D. H.
Weyl, Woldemar
Swarthmore
Kohler, Wolfgang
Swann, W. F. G.
Willis, Marion P.
Swissvale
Grondahl, L. O.
Tarentum
Pilston, Robert G.
Thomasville
Stillman, Alan H.
Towanda
Kinnear, Jean E.
Larsen, Elmer C.
Merrill, John B.
Owen, E. Robert
Upper Darby
Rice, Claude K.

Wallingford
Bazzoni, Charles B.
Warrington
Decker, John C., Jr.
Washington
Hill, Harry
Waynesburg
Riggs, Cecil O.
Wilkes Barre
Policoff, William W.
Wilkinsburg
Hill, William J.
Willow Grove
Fastie, William G.
Woodlyn
Cerato, Charles C.

RHODE ISLAND—6

East Greenwich
Driscoll, Walter G.
Kingston
Albright, John G.
Newport
Eppley, Marion
Providence
Riggs, Lorrin A.
Spencer, Domina Eberle
Warren
Rhee, Daniel

SOUTH CAROLINA—2

Columbia
Mercer, Charles F.
Easley
Martin, Robert H.

TENNESSEE—20

Chattanooga
Coulliette, J. H.
Cookeville
Smith, Richard S.
Memphis
Anderson, Karl R.
McCartney, John S.
Nashville
Slack, Francis G.
Oak Ridge
Barton, Charles J.
Brundage, William E.
Clark, Albert, Jr.
Feldman, Cyrus
Griffin, Paul M.
Hallowell, A. Lincoln
Jones, John W.
McCutchen, Roberta L.
McIntosh, W. R.
McNally, J. Rand, Jr.
O'Leary, William J.
Owen, Louis E.
Rogers, Lewis H.
Stukenbroeker, George L.
Yonts, Oliver C.

TEXAS—34

Austin
Allen, Ralph G.
Coleman, Howard S.
Coleman, Madeline F.
Crawford, George W.
Estes, William B.
Fridge, D. L.
Harmon, Darell Boyd
Hill, Otto Herman
Rosenberger, Harold E.
West, Robert B.
Beaumont
Lee, James H.
College Station
Carls, Robert J.
Silvey, O. W.
Dallas
Folsom, W. E.
El Paso
Weaver, W. R.
Fort Bliss
Price, William P.
Freeport
Weddell, W. M.
Galveston
White, Herbert H.
Houston
Collier, Ivan T.
Fagan, Herbert C.
Johnston, Robert W. B.
Kannenstine, Fabian M.
MacMahon, Andrew M.
McLean, Charles H., Jr.
Potts, Charles R.
Lake Jackson
Perry, V. G.
Lubbock
Craig, William M.
Merrymon, William Walter
Pasadena
Smith, Ivie Lee
Randolph Field
Gulley, Wayne E.
Haber, Heinz
San Antonio
Erlandson, Paul M.
Shaftan, Kenneth
Texas City
Gentry, Robert

UTAH—4

Midvale
Dusedau, Edwin W.
Provo
Marshall, Milton
Salt Lake City
Filler, Aaron
Harris, Franklin S., Jr.

VERMONT—4

Chester
Boni, Albert
Pownal
Reinheimer, Hans H.
Springfield
Finn, Robert R.
Murch, Harold L.

VIRGINIA—38

Alexandria
Brennan, J. S.
Brown, George E.
Imus, Henry A.
Katz, Moses J.
Packer, Donald M.
Platt, Joseph B.
Scott, Noel W.
Young, Clinton J. T.
Arlington
Bartelt, John A.
Belknap, Marion A.
Darr, John E., Jr.
Hunter, Richard S.
Isakson, Frank B.
Murphy, William M.
Blacksburg
Schweizer, Leslie R.
Ussery, H. D.
Charlottesville
Beams, Jesse W.
Brown, Frederick L.
Busse, Warren
Geldard, Frank A.
Holladay, Lewis L.
Hoxton, L. G.
Snoddy, Leland B.
Southall, James P. C.
Dahlgren
Hamlin, John R.
Fairfax
Fairchild, Charles O.
Larkin, Charles R.
Weiler, Harold F.
Falls Church
Jordan, Alvin B.
Fort Belvoir
Hass, Georg H.
Laufer, Jerome
Paul, Fred W.
Smakula, Alexander
Hampton
Bryant, Carroll W.
Harrisonburg
Pittman, Melvin A.
Lexington
Forster, Irving G.
Onancock
Kollmorgen, F. L. G.
University
Thiers, Ralph E.

WASHINGTON—5

College Place
Kretschmar, George G.
Pullman
Abbitt, W. H.
Seattle
Freeman, Gerald O.
Vancouver
Petrey, Arthur W.
Woodinville
Elden, Richard E.

WEST VIRGINIA—12

Alloy
Conard, John R.
Charleston
Best, William G.
Huntington
Neuhaus, C. J.
Polan, L. M.
Morgantown
Hunter, Richard G.
Molby, Fred A.
Moundsville
Allen, R. Glenn
Parkersburg
Scott, Ralph H.
St. Albans
Ross, Joseph H., Jr.
South Charleston
Williams, Dwight
Weirton
Geffner, Joseph
Steakley, W. E.

WYOMING—1

Laramie
Harding, Samuel W.

WISCONSIN—14

Appleton
Davis, Myrl N.
Steele, Westbrook
Van Den Akker, J. A.

Burlington
Turnbull, William

Janesville
Hyzer, William G.

Madison
Mack, Julian Ellis
Mote, F. A.
Wilson, Charles M.

Milwaukee
Friedlander, Mary B.
Karrer, Sebastian
Poehlman, William J.
Ruhloff, Robert A.

Ripon
Conant, George H., Jr.

Sun Prairie
Gilroy, John

Foreign Members According to Country

ARGENTINA

Capurro, Juan Jorge
Goodbar, Isaac

AUSTRALIA

Esserman, N. A.
Redies, M. F.
Westheimer, Gerald
Winsor, Keith

BELGIUM

Henroteau, Francois C.
Van Bergen, F.

BRAZIL

Vasconcellos, D. F.

CANADA

Abbey, Sydney
Allen, Frank
Bateson, Sydney
Burgener, John E.
Callon, Ross W.
Carman, P. D.
Cave, G. C. B.
Chapman, Marian H.
Conquergood, Charles R.
Crompton, Walter H.
Davison, Hedley F.
DeLury, Ralph E.
Fearnley, George
Foster, A. W.
Gibson, J. M. D.
Gilchrist, L.
Hamly, D. H.
Harrold, James
Hazel, Wallace M.
Howlett, Leslie E.
Ireton, H. J. C.
Jacobsen, Ratje C.
Kane, John
Kerr, H. S.
Laird, Elizabeth R.
Landon, Fred
Langstroth, G. O.
Lapp, Philip A.
Leigh, D. C.
Lusby, G. R.
Mayo, Eleanor G.
McLay, A. B.
Middleton, W. E. K.
Montgomery, C. E.
Morgan, J. C.
Nicholls, Ralph W.
Patterson, W. A.
Pelletier, Paul-Ed
Ruedy, Richard
Sandiford, Peter J.
Smith, Harold D.
Tate, P.
Warren, Edwin W.

CHINA

Hu, Kang Fuh

CZECHOSLOVAKIA

Vasicek, Antonin

DENMARK

Grubb, Kjeld T.

ENGLAND

Fleming, A. P. M.
Gray, W. M.
Harding, H. G. W.
Harrison, G. B.
Harrison, V. G. W.
Hay, O. G.
Hewitt, Joseph
Hill, N. D.
Holmes, J. G.
Horner, R. G.
Hugill, W.
Jarrold, H. John
Marshall, E. E. B.
Martin, Louis C.
Mather, Keith B.
Menzies, A. C.
Merton, Thomas R.
Stiles, W. S.
Taylor, A.
Taylor, Edward W.
Turner, W. E. S.

FRANCE

Castro, R. J.
Long, Bernard
Peridier, Julien
Pieron, Henri

GERMANY

Hase, Rudolph

HOLLAND

deGroot, Willem
Sanders, William G.
Van Heel, A. C. S.
Warsen, W.

INDIA

Banerjee, G. N.
Ghosh, Chandra Sekhar
Hariharan, P.
Pant, Banshidhar
Raman, C. V.
Rao, C. S.

ITALY

Bossolasco, Mario
Canina, Vittorio Garino
Gatterer, Alois
Rudatis, Domenico

JAPAN

Nagaoka, M.

MEXICO

Aguado, Alfonso Lopez
Malpica, Jose M.

PANAMA

Oldach, W. H.

SPAIN

Duran, D. A.
Otero, Jose M.

SWEDEN

Berg, O.
Mollberg, Nils

SWITZERLAND

Goldmann, Hans

VENEZUELA

Centeno, Melchor V.